

T-CHAT educational framework for teaching cyber-physical system engineering

Elena Mäkiö^a, Freeha Azmat^a, Bilal Ahmad^a, Robert Harrison^a and Armando Walter Colombo^b

^aWarwick Manufacturing Group (WMG), University of Warwick, Coventry, UK; ^bFaculty of Technology, University of Applied Sciences Emden/Leer, Emden, Germany

ABSTRACT

Cyber-physical systems (CPS) are increasingly used in manufacturing, transportation, health, and other industries. To develop these complex interdisciplinary systems, highly qualified CPS engineers are required who possess sound engineering knowledge and excellent transferable skills. Academic institutions offer a range of modules and curricula to teach CPS engineering. However, the literature reports a gap between expectations of industry and competencies of CPS graduates. To close this gap, this paper introduces and describes a holistic educational framework (T-CHAT) for teaching CPS engineering at the module level. To evaluate this framework, two use cases were analysed by conducting self-perception surveys and semi-structured interviews with students. Descriptive statistics and *t*-tests were calculated for the survey data. Interviews were coded and analysed using a General Inductive Approach. The analysis results were discussed by the comparison of the T-CHAT implementations in these two use cases.

ARTICLE HISTORY

Received 26 February 2021

Accepted 11 November 2021

KEYWORDS

CPS engineering education; T-CHAT educational framework; perceptual learning; project-based learning; problem-based learning

1. Introduction

CPS, which are highly complex interdisciplinary engineering systems, span across various academic disciplines of engineering, science and social sciences, such as embedded systems, sensors and communication networks, software engineering, cybersecurity, big data and artificial intelligence, physics, human factors, ethics, and law (Cheng 2014). As CPS continue to expand and affect the economic and social development of our society, the demand for qualified engineers and experts being capable of developing, operating, maintaining, and managing CPS is increasing (National Academies of Sciences 2015).

Although CPS engineering is an emerging field, industry and society have defined their expectations and requirements for establishing CPS education and qualifications that engineers need to have to succeed in their profession, and what knowledge and skills are not sufficiently developed after completing engineering education (see DECOS 2007; Schoitsch 2014; CyPhERS 2015; National Academies of Sciences 2015; Törngren et al. 2015; Mäkiö-Marusik 2017; National Academies of Sciences 2016; Henshaw and Deka 2018; Mäkiö-Marusik et al. 2018). These studies have come to the common conclusion that CPS engineers need to have a holistic view of CPS, sound skills in CPS engineering foundations and non-functional characteristics of CPS, pronounced social and methodological skills. A competence gap has been identified in the holistic understanding of CPS, social and business skills, cross-disciplinary and critical thinking, and creativity.

CONTACT Elena Mäkiö  E.Makio-Marusik@warwick.ac.uk

© 2021 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.

Academic institutions respond to the demands of industry and society for CPS talent and have recently developed several CPS modules and programmes (see examples in National Academies of Sciences 2016; Mäkiö-Marusik 2017). Explorations in CPS education started by introducing new CPS-related modules to the existing electrical engineering and computer science programmes, such as by Lee, Seshia, and Jensen (2013) at the University of California, Berkley, in 2008, by Taha et al. (2017) at Halmstad University. Chen, Damevski, and Edwards (2013) infused CPS-related content into the existing computer science curriculum to provide continuous gradual integration of CPS concepts. CPS-related content was also incorporated into the existing or newly created programs in specific engineering fields, such as in aerospace engineering (Atkins and Bradley 2013), mechatronics (Plateaux et al. 2016), civil and environmental engineering (see National Academies of Sciences 2015). Various academic institutions developed new CPS engineering curricula, mainly on the master level (see Lieu Tran et al. 2019).

Various educational approaches are used in the new CPS modules (Mäkiö-Marusik 2017), such as project-based learning (PjBL), and lectures and labs (Grega and Kornecki 2015; Plateaux et al. 2016; Wade et al. 2015; Salewski and Schmidt 2015), which are traditionally used for teaching engineering disciplines. Learning factories, modelling and simulation environments and their online implementations present a widely used technical tool to introduce CPS engineering practice to students (Marwedel and Engel 2014; Kim et al. 2016; Taha et al. 2016; Pechmann et al. 2019). However, the existing CPS modules and teaching approaches mainly focus on imparting specific technical knowledge and skills, ignoring the full range of transferable skills required. In addition, there is a lack of knowledge and understanding of the pedagogical approaches that can be used to impart these competences to students, and of how these approaches can be systematically applied to the design and construction of modules (Felder, Brent, and Prince 2014). Despite launching various CPS engineering curricula and modules, the skill gap remains between expectations of industry and CPS engineering graduates (National Academies of Sciences 2015, 2016; Mäkiö-Marusik 2017; Mäkiö-Marusik et al. 2018).

In this paper, we present a solution to fill the gaps that have been identified in the current CPS engineering education at the module level by answering the following research questions:

- What disciplinary and transferable competencies are required of graduate cyber-physical systems engineers?
- How to train these competencies? What educational approaches and methods need to be used at the module level and how do these approaches need to be combined?

For this, we introduce and evaluate the T-CHAT educational framework, which (1) aims to develop disciplinary knowledge and transferable competencies of students and (2) provides guidance and tools for teachers to design and organise their modules. The T-CHAT framework combines five pedagogical approaches: (1) perceptual learning, (2) project-based learning, (3) problem-based learning, (4) research-based learning, and (5) face-to-face teaching (for details, see Mäkiö, Mäkiö-Marusik, and Yablochnikov 2016) in a learning process, as they fill the gaps of each other and a holistic/synergistic outcome is achieved through their combination and linkage.

This paper first outlines the existing literature in the field, subsequently describes the T-CHAT educational framework and the methodology used. Finally, the results are presented and discussed before concluding.

2. Literature review

2.1. Industry expectations and requirements on competencies of CPS engineering graduates

Various research studies and government initiatives were conducted to acquire insights into the required qualifications specific to the CPS workforce and skill gaps (National Academies of Sciences

2015, 2016; Schoitsch 2014; DECOS 2007; CyPhERS 2015; Törngren et al. 2015; Henshaw and Deka 2018; Mäkiö-Marusik 2017; Mäkiö-Marusik et al. 2018; Colombo et al. 2020). The identified competencies can be divided into disciplinary competencies and key competencies (also referred to as generic competencies/skills, transferable skills). While disciplinary competencies are specific for the profession of CPS engineers, key competencies are general and can be classified into four categories according to Orth (1999):

- social competence (e.g. the ability to communicate and collaborate),
- personal competence (e.g. responsibility, self-esteem, leadership),
- systematic competence (e.g. problem-solving and analytical skills), and
- general competence (e.g. project management, information technology).

The required competencies (Table A1) can be summarised as follows:

- Since the development of CPS spans across various academic disciplines of engineering, science and social sciences, cross-disciplinary competence and multidisciplinary awareness of CPS engineering are necessary for CPS engineers. CPS students should develop a holistic, broad view of CPS. They must have a competent, broad understanding across several CPS-related subjects and sound knowledge of their area of specialisation.
- Competence in CPS foundations and principles is highly appreciated.
- Competence in non-functional characteristics of CPS is required for the successful development of CPS.
- Social competencies, including the ability to work well in interdisciplinary teams, effective communication, presentation and technical writing, are required due to the interdisciplinary nature of CPS and the growing complexity of systems.
- Systematic competencies, such as critical thinking, analytical and problem-solving skills, are required for CPS engineers.

The competence gaps (Table A2) include the following:

- a holistic understanding of CPS, broad system perspective and understanding of the complete heterogeneous systems,
- CPS security and privacy topics,
- social competencies such as collaboration and communication skills,
- cross-disciplinary thinking, entrepreneurship, critical thinking and creativity, and
- project management.

While key competencies are significant to effective engineering work, scientific engineering knowledge is primarily required, which forms the basis for the development of the former (see Winberg et al. 2020).

2.2. Addressing the required qualifications and competence gap

The area of CPS engineering education is evolving and, therefore, offers educators the opportunity to tailor curricula, courses and teaching, including pedagogical approaches and methodology, to meet the needs of the industry and society.

A literature review (Mäkiö-Marusik 2017) revealed that educators offer several CPS modules and use versatile pedagogical approaches. These approaches include both traditional teaching methods, such as lectures and labs, and pedagogical approaches introduced to engineering education in the last decades of the twentieth century, such as project-based learning (PjBL), problem-based learning (PBL) (for PjBL and PBL, see Kolmos 1996; Mills and Treagust 2003) and research-based learning (RBL)

(Healey and Jenkins 2009). PjBL and a combination of lectures and labs are most popular in CPS engineering modules. PjBL as a single approach is used, for instance, in the modules of Crenshaw (2013), Grega and Kornecki (2015), Lawlor et al. (2015), Plateaux et al. (2016) and González and Calderón (2018), lectures and labs in the modules of Bauer and Schneider (2013), Damevski et al. (2013), Helps and Pack (2013), Peter, Momtaz, and Givargis (2015) and Kim et al. (2016). PjBL is often combined with lectures and labs, such as in the modules of Salewski and Schmidt (2015), Cancila et al. (2016), Leitão et al. (2016) and Taha et al. (2017). PBL, not as popular as PjBL, is used in the module of Veza, Gjeldum, and Mladineo (2015) as a standalone approach and also in combination with PjBL in the modules of Simons, Abé, and Naser (2017), Laird (2016) and Ikonen et al. (2009). RBL is used in combination with PjBL (Thiede, Juraschek, and Herrmann 2016) and PBL (Bertels et al. 2009).

The use of various teaching approaches in CPS engineering education is rarely evaluated in the empirical research literature. Ten of 22 examined research studies presenting various CPS modules did not evaluate them (Grega and Kornecki 2015; Plateaux et al. 2016; Damevski et al. 2013). The majority of the remaining studies collected student feedback at the end of the module and presented it in text form (Salewski and Schmidt 2015; Simons, Abé, and Naser 2017; Taha et al. 2017). Helps and Pack (2013) measured students' technical background and their knowledge of CPS before and after the module and reported an increase of average values without analysing its statistical significance. Verbic, Keerthisinghe, and Chapman (2017) measured student learning experience and their capability to successfully complete a project, development of generic skills, and overall satisfaction with the team project, but found no statistically significant improvement. All studies report very positive student feedback and high student satisfaction with modules, whereas no empirical study in CPS engineering education evaluates the improvement of student competencies or compares the teaching approaches used with alternative pedagogical approaches.

Despite efforts to improve CPS education and the various educational approaches used in CPS modules, the skill gap remains between the expectations of the industry and engineering graduates. Given the above pedagogical approaches, the question arises whether they adequately address the required competencies of CPS engineering students.

2.3. Pedagogical approaches

Several pedagogical approaches for the development of a broad variety of competencies can be found in the literature. Four pedagogical approaches – project-based learning (PjBL), problem-based learning (PBL), research-based learning (RBL) and face-to-face teaching (F2F) (in this study, this means the traditional one-way transmission of content in lectures and activating techniques of small group teaching in seminars and labs) – were critically analysed with regard to teaching practice in a literature review. The following two sections explain how these approaches address the development of the competencies that CPS engineering graduates need to have and how they fill in the gaps of one another.

2.3.1. Addressing the competencies

According to the constructivist theory of learning, students play an active and main role in acquiring knowledge and developing competencies (Westwood 2008). The role of teaching is to use appropriate pedagogical approaches and teaching methods to help students learn and promote learning activities that facilitate the development of their competencies. Theoretical works, reviews of the literature, and empirical studies in engineering education related to the four pedagogical approaches were examined to understand which of these approaches are suitable from both a theoretical and practical point of view to encourage students to develop the competencies required. Table A3 summarises a mapping of these competencies (in rows) and the pedagogical approaches (in columns).

The application of pedagogical approaches depends on the learning objectives and on the current level of students' knowledge. The acquisition of initial knowledge is more efficient through direct teaching and advanced and expert knowledge through constructivist methods

(Westwood 2008). The acquisition of theoretical knowledge can be efficiently facilitated by direct presentations during lectures, while the development of higher-order cognitive skills (refer to Bloom's taxonomy of cognitive domain in Anderson and Krathwohl 2001) can be better triggered by constructivist approaches (Westwood 2008). PjBL and PBL that correspondingly deal with application and acquisition of knowledge through hands-on activities in a team are suitable to the CPS engineering practice (Mills and Treagust 2003; Kolmos 1996).

PjBL and PBL approaches contribute to the development of social competencies such as collaboration and communication (Arana-Arexolaleiba and Zubizarreta 2017; Lima et al. 2017; Verbic, Keerthisinghe, and Chapman 2017; Johnson and Ulseth 2017). PjBL used in engineering education triggers the improvement of the ability to write technical documents (Johnson and Ulseth 2017; Arana-Arexolaleiba and Zubizarreta 2017). RBL in the form of literature-based inquiry also fosters competence in technical writing (Aditomo et al. 2013). Creative thinking can be promoted by some learning activities of small group teaching (Race 2014) and in RBL (Deakins 2009). Systematic, or methodological competencies, such as analytical and critical thinking, can be enhanced during learning activities of PjBL, PBL, and RBL (Dochy et al. 2003; English and Kitsantas 2013; Knetsch and Cleij 2017).

To conclude, the alignment of pedagogical approaches to the competencies of CPS engineers revealed the following:

- Different approaches contribute to the development of different competencies in CPS engineering students. When applied individually, these approaches are not suitable to enhance all the necessary competencies.
- The pedagogical approaches fill in the gaps of one another. Therefore, a combination of them enables the development of the entire range of competencies that CPS engineering students must have.

2.3.2. Minimising individual disadvantages

A combination of the four pedagogical approaches – project-based learning (PjBL), problem-based learning (PBL), research-based learning (RBL) and face-to-face teaching (F2F) – can minimise disadvantages that occur when these approaches are used individually or combined in the well-known way, for instance, PBL combined with PjBL in engineering education (Kolmos, Fink, and Krogh 2004).

The main positive aspect of the PBL and PjBL is that students acquire and directly apply knowledge in professional practice and, thus, experience increased motivation (Kolmos and Graaff 2014). Moreover, students taught using the PBL and PjBL achieve deep learning and higher-order cognitive skills (Dochy et al. 2003) and better develop their key competencies in teamwork, communication, social responsibility, contemporary issues and management than students being taught using traditional methods (Kolmos, Holgaard, and Clausen 2021).

However, there are some critical findings and facts about these approaches. According to Kirschner, Sweller, and Clark (2006), the quality of learning by students who participated in PBL is not higher than the students taught by traditional guided methods, whereas the risk in lack of disciplinary knowledge is high. Since PBL focuses on solving authentic problems, no sufficient academic overview is gained (Kolmos and Graaff 2014). The hierarchical structure of engineering knowledge requires that topics have to be learned in certain order to understand key concepts of the discipline (Mills and Treagust 2003). Since PBL cannot guarantee this, in engineering, this may lead students to construct the wrong knowledge and/or a lesser understanding of engineering fundamentals. The recent longitudinal study of Kolmos, Holgaard, and Clausen (2021) has shown that students taught using the PBL and PjBL assessed themselves as being less prepared for engineering work than the traditionally taught students in terms of fundamental engineering knowledge and skills, such as engineering and data analysis, maths and science, engineering tools, and conducting experiments. It is also worth noting that there is no significant difference in student perceptions of their

preparedness to use problem-solving skills, engineering design, creativity, leadership, and lifelong learning in their engineering practice by both groups of students.

Therefore, the sole use of constructivist approaches, such as the combination of PBL/PjBL for the teaching of CPS engineering does not address the development of the main competencies required that include (1) the profound academic knowledge and theoretical understanding of the disciplinary fundamentals and (2) the broad cross-disciplinary understanding of CPS engineering with a variety of technological and societal requirements, i.e. a holistic view. The former can be more efficiently transmitted to students using lectures, group work and assignments (Westwood 2008). A combination of these instructional teaching methods with PBL and PjBL results in a guided acquisition of the theoretical knowledge through teaching, self-directed learning in PBL, and applying the acquired knowledge when performing a project. What concerns the latter, the authors of this article believe that problem solving and gaining a wider view on CPS engineering contradict each other since solving concrete problems does not broaden students' view of overall system engineering (see Barnett 1994). The combination of PBL/PjBL does not support students in overcoming troublesome points in their learning (referred to as threshold points (Meyer and Land 2003)) that open 'a new and previously inaccessible way of thinking about something' (1). For instance, understanding the synergy of physical entities and the cyber part of CPS represents a threshold concept in the CPS engineering discipline.

CPS engineers are required to work and think independently (see required competencies in Table A1), which is not addressed through PBL or PjBL. Since during teamwork the responsibility lies with the entire team and not with an individual; the ability to work and think independently is not enhanced to the same extent as in research-based learning (RBL) and F2F teaching (see Table A3). In CPS engineering, research innovation and application of engineering knowledge are blurred because novel research results are immediately applied. The ability to innovate, which is important for CPS engineering graduates, can be developed using RBL.

2.4. Perceptual approach

The perceptual approach (Kurki-Suonio 2011) has influenced the development of the T-CHAT educational framework and serves as its background. This approach is based on the idea 'perception plays a fundamental role in all learning' (Kurki-Suonio 2011, 212). Perception is an intuitive, non-conscious process of creating meanings based on empirical observations and interpretations. The perceived meanings are placed in an existing mental structure; then they can be conceptualised and placed in an existing conceptual hierarchy. Perceptual learning thus progresses from observations and experiments to understanding and conceptualising, moving from the lower levels of the conceptual hierarchy to the higher ones. Knowledge and understanding are constructed by each learner individually from their personal perspective, then they are refined and confirmed through collaboration and communication within a learning community. This concept of constructing new knowledge and social interaction and communication corresponds to the ideas of 'social constructivism' (see Vygotsky 1978).

To find a correct starting level for teaching, it is necessary to determine the initial level of knowledge of students. The existing relevant knowledge, students' own observations and everyday experiences have to be considered in teaching. Versatile pedagogical approaches are applied to support perceptual learning, for instance, peer discussions can be used for describing students' observations, and identifying and formulating their own ideas; learning and working in groups provide a social component; project-based learning is used to apply knowledge (Mills and Treagust 2003).

2.5. Summary

The pedagogical approaches used in CPS engineering modules do not or only partially address the development of the required competencies of CPS engineering students. To address the entire range

of the competencies, a combination of various approaches is needed. The four pedagogical approaches – project-based learning (PjBL), problem-based learning (PBL), research-based learning (RBL) and face-to-face teaching (F2F) – fill the gaps of one another by

- developing the required competencies of CPS engineering students, and
- counteracting the disadvantages of one another.

These pedagogical approaches with the perceptual approach are integrated into the T-CHAT educational framework.

3. T-CHAT educational framework

To respond to the growing demand of the industry and society for the qualification of CPS engineering graduates, the task-centric holistic, agile teaching approach T-CHAT was introduced (Mäkiö, Mäkiö-Marusik, and Yablochnikov 2016) as an integrated educational approach at the module level. Since then, this approach has been grounded, improved and extended to the T-CHAT educational framework through an inductive integration of literature, and analysing and gathering more experience through its implementation in several modules related to CPS. T-CHAT framework involves the competencies and skills required of CPS engineering graduates (see section 2.1) and the T-CHAT learning process.

3.1. T-CHAT learning process

The T-CHAT learning process efficiently integrates and combines the five strands of T-CHAT (1) perceptual learning (**PerL**), (2) project-based learning (**PjBL**), (3) problem-based learning (**PBL**), (4) research-based learning (**RBL**), and (5) face-to-face (**F2F**) teaching at the module level and ensures that the students achieve the intended learning outcomes. The results of the literature review on learning activities, assessments, benefits and drawbacks of these pedagogical approaches, and successful learning and teaching served as the basis for the definition of the T-CHAT learning process.

Figure 1 schematically shows the use of the individual pedagogical approaches within a module over time (X-axis) and student progress towards learning outcomes (Y-axis). These approaches are

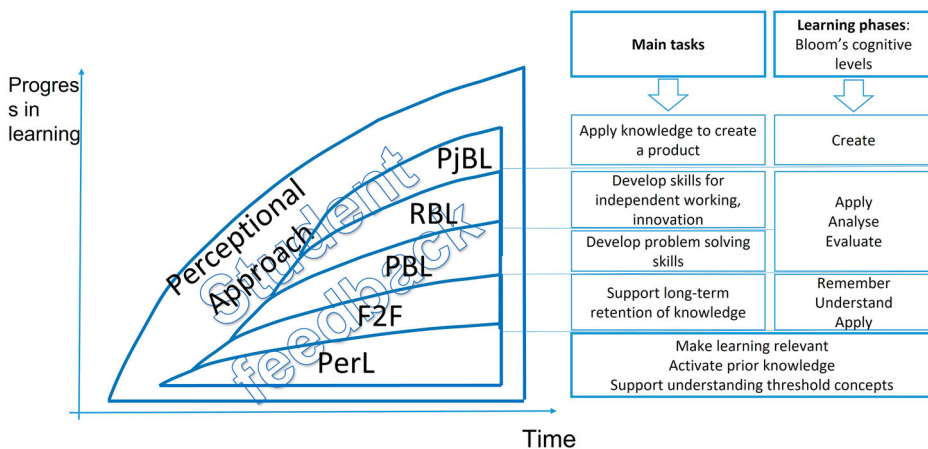


Figure 1. T-CHAT Learning Process (own elaboration). PerL: perceptual learning; F2F: face-to-face teaching; PBL: problem-based learning; RBL: research-based learning; PjBL: project-based learning.

mapped to their main objectives and learning phases, which correspond to Bloom's six cognitive levels in the development of intellectual abilities and skills (Anderson and Krathwohl 2001). The perceptual approach to teaching in Figure 1 permeates the entire T-CHAT learning process and ensures that perceptual learning takes place. The creation of hierarchically layered knowledge from the simple to the complex goes hand in hand with Bloom's six cognitive levels. To enable this development, the perceptual approach to teaching embeds the other four pedagogical approaches (see Figure 1) that pursue different goals in the development of intellectual skills and key competencies.

The learning process starts with the PerL. To make learning relevant for students, activate their prior knowledge and experience to incorporate new knowledge into the existing cognitive structure and provide a big picture, the instructional tool Advanced Organiser (Ausubel 1963) is used. A big picture and an intuitive understanding of the subject matter are provided by discipline-typical examples and observations from everyday life. Learning of threshold concepts (Meyer and Land 2003) of CPS engineering, for instance, understanding of emergent behaviour of CPS, are supported by giving the students examples that facilitate their understanding and an opportunity and time to reflect.

At F2F teaching, brief presentation phases (up to 20 minutes), during which a teacher presents discipline-specific content to students and explains the subject matter, are mixed with individual and group activities that involve students in doing and exploring new things, asking questions and discussion. By doing so, the main disadvantage of lectures may be avoided, namely, taking away responsibility for learning from students and encouraging their passivity (Race 2014). Simultaneously, their benefits can be focused on providing a shared learning experience and a learning focus to the students (Race 2014). Individual classes are structured based on the sandwich principle in which phases of plenary presentations, group work and individual learning activities are connected by plenary discussions and reflection (Kadmon et al. 2008). Student feedback and observation are key instruments to adapt the learning process in each class to the needs of students. The complex topics the students struggle with are explained slowly, while the simpler topics are dealt with more quickly.

At the next learning phase of achieving the cognitive levels: Apply, Analyse, and Evaluate, PBL is added to the T-CHAT learning process. After disciplinary foundations were presented to the students in PerL and F2F teaching, students are empowered to expand theoretical knowledge and develop problem-solving skills and the ability to think analytically and critically. To promote interdisciplinary learning (De Graaff and Kolmos 2003; Kolmos, Fink, and Krogh 2004) and help the students gain a broad multidisciplinary understanding (Barrows and Tamblyn 1980), real-life problems are given to students. The task must be challenging for students, not too easy and not too complex, that means it must lay in a zone between the existing ability to independently solve it and the potential ability to solve it under assistance (see 'zone of proximal development' in Vygotsky 1978).

RBL is added to the T-CHAT learning process to reinforce the ability to work and think independently and enable students to actively learn and practice novel research topics, methods and processes. Since the boundaries between research and application of research results in engineering domain are blurred, students need to learn how to make research in order to be employable and successful in the profession. RBL is organised as literature- or discussion-based inquiry (Aditomo et al. 2013).

PjBL is added to the T-CHAT learning process after students have become mature with the subject. In PjBL, students apply the new knowledge in professional practice when working on a task that covers interdisciplinary specifics of CPS and, thus, triggers the development of interdisciplinary competence. In addition to acquiring engineering practice, students enhance their social competencies such as collaboration and communication, leadership skills, and project management.

Student feedback is regularly obtained during the T-CHAT learning process and is used to adapt the teaching to the needs of the students.

4. Evaluation

The impact of the T-CHAT educational framework on students learning was evaluated using a mixed-methods research methodology.

4.1. Research method

The mixed-method sequential explanatory design (Creswell and Creswell 2009) was conducted in this study that consists of two consecutive phases of collecting and analysing data: a quantitative phase and a qualitative phase. Quantitative data were collected on how students self-assessed the improvement of their competencies through surveys. The survey results informed the qualitative phase with semi-structured interviews with volunteer students.

In the quantitative research phase, the T-CHAT educational approach was compared to alternative educational methods using the quasi-experimental non-randomised approach (Anderson and Arsenault 2005) and the non-equivalent comparison group design with no pre-test (Shadish and Luellen 2006). Based on this design, the following experiment was designed and carried out:

1. The selected module in its original form was delivered. Participants of this module served as a control group.
2. The same module, but now redesigned using the T-CHAT approach, was delivered. Participants of this module served as a treatment group.
3. Both modules were evaluated at the end by carrying out self-assessment surveys to measure the increase in students' competencies, not their absolute level.

Students enrolled for the first or second module delivery automatically belonged to the control or treatment group, respectively. Since the students in the control and treatment groups studied in the same semester, it was assumed that, on average, both groups had the same levels of disciplinary and transferable competence prior to the module. Both deliveries of the module in the experiment were carried out by the same teachers who were supported in implementing the T-CHAT approach. An evaluation instrument (see Evaluation instrument) developed within the scope of this research was used to collect quantitative data (Mäkiö-Marusik et al. 2019).

In education research the quantitative methods with significance testing usually have the drawback that their findings are either mixed or non-significant, statistically and educationally (Anderson and Arsenault 2005). Thus, to counteract this drawback, to better understand students' responses in the self-assessment survey and provide explanations for possibly unexpected results, semi-structured interviews (Denzin and Lincoln 2017) with students were carried out (questions see in Questions of semi-structured interviews with students). In contrast to the survey, the user-oriented evaluation identified the concerns and positive effects only when the students articulate their experiences and views with their own words.

4.2. Evaluation instrument

The evaluation instrument measures students' perception of the improvement of competencies, the motivation and learning process in modules using a questionnaire with the items located on a 5-point Likert-type scale: 'Definitely agree' = 5, 'Mostly agree' = 4, 'Neither agree nor disagree' = 3, 'Mostly disagree' = 2, 'Definitely disagree' = 1. It has the following factors:

1. Disciplinary competence (questions 1–8),
2. Social competence (questions 9–15),
3. Systematic competence (questions 16–20),
4. Personal competence (question 22),

5. General competence (question 21),
6. Learning process (questions 23–31), and
7. Motivation (questions 32–36).

The content and construct validity and reliability in terms of the intra-class correlation and the internal consistency of the instrument were calculated in the previous study of Mäkiö-Marusik et al. (2019).

4.3. Data analysis

The data gathered through the questionnaire were analysed for the factors 1–7 (see 4.2) using IBM SPSS statistical software. There were two independent samples from two populations in the experiments – the control and the treatment group. To examine the summary of student responses, descriptive statistics, such as the number of cases, mean, standard deviation, were calculated for each group. Independent samples *t*-tests were performed for the factors 1–7 to evaluate whether there was a statistical difference between the associated population means. *T*-tests are appropriate and reliable for Likert scores even if normality is moderately violated (De Winter and Dodou 2010). The alternative hypothesis was tested that the scores were higher in the treatment than in the control group. Therefore, one-tailed *t*-tests were used. The significance level of statistical tests is reported using the following notation: † when $p < .1$, *when $p < .05$, **when $p < .01$ and ***when $p < .001$. Cohens' *ds* and Hedges' *gs* (for sample sizes < 20) were estimated to measure effect size as practical significance and impact of the T-CHAT educational intervention on student learning.

Hattie (2008) provides a useful benchmark for evaluating such impacts. The average effect size of educational interventions is 0.4. Effect sizes of less than 0.2 indicate a lack of teaching, effects between 0.2 and 0.6 mean medium teaching effects, and those greater than 0.6 are considered large when judging educational outcomes. For instance, for problem-based learning (PBL) educational interventions, a statistical analysis of literature made by Dochy et al. (2003) identified that PBL has a robust positive effect of 0.460 on the skills and a significantly negative effect of -0.223 on the knowledge of students.

The interviews were recorded, transcribed, coded and finally analysed using a General Inductive Approach (Thomas 2006) and qualitative data analysis software Nvivo to uncover and describe the most important categories and themes. When coding, the qualitative data were reduced and analytically categorised. Based on this categorisation, qualitative explanations and generalisations were developed that remain close to concrete data and contexts but go beyond simple summary descriptions of the data (Neuman 2014). Therefore, the quantitative and qualitative results can be transferred to other similar situations and other similar groups of students.

4.4. Use cases

Two modules conducted at the University of Applied Sciences Emden/Leer (Germany) were explored as use cases for this study: (1) the 'Programming' module in the Bachelor program in Computer Science (see Mäkiö et al. 2020) and (2) the 'Engineering of Industrial Cyber-Physical Systems (ICPS)' module in the Master program 'Industrial Informatics – Specialisation Industrial Cyber-Physical Systems' which is a consecutive degree to the Computer Science and Electrical Engineering Bachelor programmes (University of Emden/Leer n.d.; Wermann et al. 2015; Colombo et al. 2020). Table 1 summarises the main features of these modules.

4.4.1. Module 'Programming'

For our experiment, the 'Programming' module was delivered twice: in the winter term 2018–2019 (the control group) using traditional teaching methods and in the winter term 2019–2020 (the treatment group) using the T-CHAT approach. The main learning outcomes of this module are that the

Table 1. The main properties of the modules.

Properties of modules	Programming	Engineering of Industrial Cyber-Physical Systems
Credits	5 ECTS credits	5 ECTS credits
Study year	1	4
Student cohort	Undergraduate students	Master students
Student study hours	150 (60 hours of teaching and 90 hours of self-guided study)	150 (60 hours of teaching and 90 hours self-guided study)
Activity types	Lectures and practical exercises	Lectures, practical exercises
Traditional teaching	Winter term 2018–2019	Winter term 2019–2020
Number of responses in the control group	56 students (out of 60)	7 students (out of 11)
T-CHAT teaching	Winter term 2019–2020	Winter term 2020–2021
Number of responses in the treatment group	42 students (out of 45)	8 students (out of 12)

students learn the core knowledge and concepts of the discipline and can apply them individually and in a team to solve simple, complex and comprehensive programming tasks. The relevance to CPS education was established through specific CPS-tailored assignments and the project task.

Table 2 lists the similarities and differences (in relation to lectures and labs) in teaching between the control and treatment groups.

Traditional teacher-centred teaching was organised in lectures and labs that were thematically related and aligned to each other. During the lectures, new concepts were briefly introduced, followed by multiple illustrative examples. Student activities, such as quiz questions and individual assignments, were incorporated into these presentations. During the labs, students performed tasks, often in groups. Quizzes and programming assignments during labs showed that the students had difficulty understanding core concepts and applying the knowledge they had acquired to solving non-trivial programming tasks.

Student-centred teaching in the treatment group was aimed at addressing these deficiencies and was organised according to the T-CHAT learning process (see Section 3.1), including all educational approaches. Perceptual learning (PerL) was used to first provide a big picture and an intuitive

Table 2. Similarities and differences between the control and treatment groups in the ‘Programming’ module.

	Control group	Treatment group
Similar variables	<ul style="list-style-type: none"> • Student cohorts • Teacher • Student study hours • Module syllabus • Summative assessment 	<ul style="list-style-type: none"> • Student cohorts • Teacher • Student study hours • Module syllabus • Summative assessment
Different variables in relation to lectures	<ul style="list-style-type: none"> • A strict teaching process aimed to convey the required subject-specific content. • Quizzes and individual assignments aimed to activate students’ attention during the lecture. 	<ul style="list-style-type: none"> • Students’ prior knowledge and experience were activated using an Advanced Organiser. • The lessons were structured according to the sandwich principle. Group and individual work, plenary presentations and discussions were mixed. • A big picture was provided using an advanced organiser and giving subject-typical examples and observations from everyday life. • Threshold concepts were comprehensively explained using subject-typical examples and observations from everyday life. They were consolidated by solving practical problems. • Student feedback was collected after each lecture to inform and adapt further F2F teaching (flexible teaching).
Different variables in relation to labs	Assignments of increasing difficulty and thematically aligned to the lectures were performed individually and in groups.	Assignments and problem tasks of ‘zone of proximal development’ were performed. A research-based learning activity was then carried out. Subsequently, project teams started to work on a project task.

understanding of the subject matter through multiple discipline-typical examples, tasks, and observations from everyday life. Subject-specific content was introduced to the students in brief presentations (F2F), mixed with group work, individual tasks and quiz questions. Particular attention was paid to the threshold concepts, such as variables and their scope, procedural decomposition and design, recursion, and return values, (see Kallia and Sentance 2017) that were introduced using PerL (see Section 2.4). During labs, students solved problems (PBL) to expand the theoretical knowledge acquired and make it applicable and useful. Students also conducted a literature-based inquiry on a topic that does not require programming (RBL). At the end of each class students were asked to give feedback that was used to adapt teaching. During the last 2/3 of the module, students worked on a project task in groups of 3–5 people (PjBL). Students developed technical documentation of their project solutions and presented the results at the end of the module.

4.4.2. Module ‘Engineering of industrial cyber-physical systems’

‘Engineering of Industrial Cyber-Physical Systems (ICPS)’ is an interdisciplinary module offered to master students with different backgrounds and different stand of knowledge and skills. It consists of two sub-modules ‘Mathematical Modelling of ICPS’ and ‘Lifecycle Engineering of ICPS’ taught by two teachers. The latter was delivered and evaluated using traditional teaching methods for the control group in the winter term 2020–2021 and using the T-CHAT approach for the treatment group in the winter term 2021–2022. The main learning outcomes of this sub-module are that the students learn various dimensions of the product and production system engineering lifecycle that are relevant for engineering ICPS and can apply this knowledge for modelling, analysis, validation and prototype implementation of ICPS. The theoretical part, including several complex and comprehensive topics, is quite large for the scope of a module, which is a challenge for teaching.

Table 3 lists the similarities and differences (in relation to lectures and labs) in teaching between the control and treatment groups.

In traditionally taught teacher-centred classes, subject-specific content was presented to students by means of lectures without interactive teaching methods. At the end of the module, the teacher elaborated and presented the example of ‘Drinking water and wastewater’ system of ICPS to prepare

Table 3. Similarities and differences between the control and treatment groups in the ‘Engineering of ICPS’ module.

	Control group	Treatment group
Similar variables	<ul style="list-style-type: none"> • Student cohorts • Teacher • Student study hours • Module syllabus • Summative assessment • Project-based learning (PjBL) with the similar project tasks 	<ul style="list-style-type: none"> • Student cohorts • Teacher • Student study hours • Module syllabus • Summative assessment • Project-based learning (PjBL) with the similar project tasks
Different variables in relation to lectures	<ul style="list-style-type: none"> • A strict teaching process aimed to convey the required subject-specific content. • The main principle: the more technical content, the better for the students. 	<ul style="list-style-type: none"> • Students’ prior knowledge and experience were activated using an Advanced Organiser. • The lessons were structured according to the sandwich principle. Group and individual work, plenary presentations and discussions were mixed. • A big picture was provided using an Advanced organiser and giving subject-typical examples and observations from everyday life. • Threshold concepts were comprehensively explained using subject-typical examples and observations from everyday life. They were consolidated by solving practical problems. • Student feedback was collected during lectures to inform and adapt further F2F teaching (flexible teaching).
Different variables in relation to labs	Assignments of increasing difficulty and thematically aligned to the lectures were performed individually and in groups.	Assignments and problem tasks of ‘zone of proximal development’ were performed.

students for their own project work. Students carried out a project (in groups of 2 or 3) to examine, analyse, describe and present a real-life system of ICPS. The project work showed that the students had difficulties understanding and applying the core concepts of the discipline, such as a process-driven behaviour of systems of ICPS and the mechanisms of emergency and system stability.

To address these deficiencies and consider the issues of using the T-CHAT approach in the 'Programming' module, student-centred teaching in the treatment group was organised according to the adapted T-CHAT learning process. The authors took the risk of not sufficiently triggering the development of systematic competencies in the students and due to time constraints and a high activity load, dispensed with research-based learning activities (RBL). Teaching in the treatment group began with activating the students' prior knowledge and experience, triggering an intuitive understanding of the subject matter, and motivating students to learning (PerL). The subject-specific content and key information were briefly presented, followed by group activities in which the students applied the new knowledge to the example of 'Drinking water and wastewater' system of ICPS (F2F). Threshold points, such as emergent behaviour of CPS, were introduced using PerL (see section 2.4). Based on the acquired theoretical foundations, the students solved specific problems to expand their knowledge and make it applicable (PBL). Student feedback was collected to adapt future learning activities. At the end of the module, students carried out projects similar to those in traditional teaching to examine and analyse a real-life system of ICPS, prepared a technical system report and presented the results of their work (PjBL).

5. Results

5.1. Module 'Programming'

5.1.1. Results of the quantitative study

Student self-perception surveys resulted in the sample sizes of 56 respondents for the control and 42 respondents for the treatment group, which shows a response rate of 93%. A score for each factor of the questionnaire (see 4.2) was calculated based on the average of student responses to the questions assigned to this factor. Figure 2 shows the distributions of the control and treatment groups that have some outliers. Data in the control and treatment groups were assessed for multivariate outliers using a Mahalanobis Distance Test (Tabachnick and Fidell 2007). Two multivariate outliers were identified and removed.

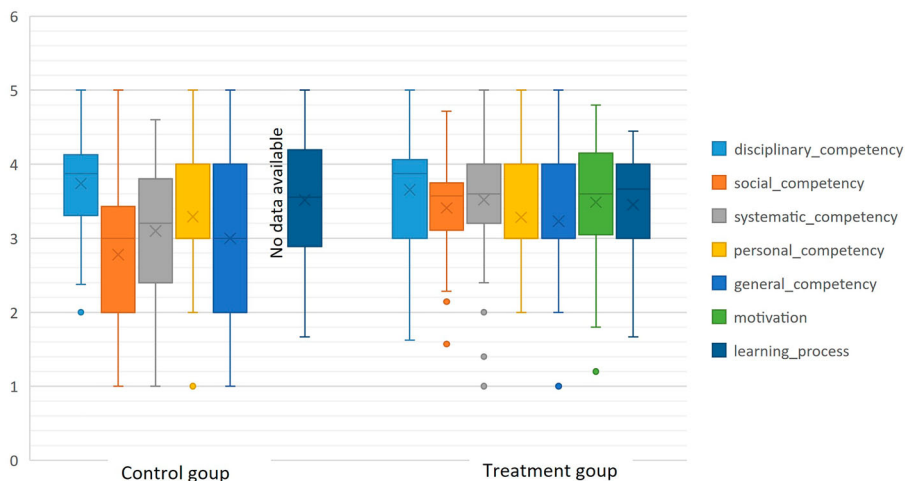


Figure 2. Box plot comparing the scores of control and treatment groups in the module 'Programming' per factor (mean value indicated by a cross). The 1.5 interquartile range (IQR) convention is used for the whiskers and the outlier identification.

The effective differences within factors between the control and treatment groups were statistically assessed, effect sizes (Cohens' d) were estimated. Table 4 summarises this analysis along with the mean and standard deviation for each factor. The results show a significant increase due to the T-CHAT intervention on social ($p < .001$), systematic ($p < .01$), and general ($p < .1$) competence. The practical significance of the T-CHAT educational intervention indicates a large effect for the factors 'Social' and 'Systematic' competence and a medium effect for the factor 'General' competence (Hattie 2008). An unexpected result is that the students in the treatment group perceived the development of disciplinary competence at the same level as in the control group and that their responses were more dispersed.

5.1.2. Results of the qualitative study

To better understand students' perception of improving their competencies during the T-CHAT intervention, six volunteer students (out of 42) were interviewed. We aimed to examine what the students perceived with regard to the development of their disciplinary competence and how they experienced the new learning process, since both factors did not show any statistically significant improvement. While interviews contained several questions on different topics, the coding of the transcribed interviews focused on these two areas of interest. Two categories were identified for each area (see Figure 3). The four categories and their associated themes are used as a framework for summarising students' perceptions.

The interviewees were heterogeneous in terms of the prior programming knowledge and skills and study experience. Three categories of prior knowledge were defined: (1) no prior programming knowledge (three interviewees); (2) basic knowledge and little experience in a programming language other than Java (two interviewees); and (3) intermediate knowledge and experience in Java and in another programming language (one interviewee). All the interviewed students had some prior study experience: four participated in apprentice programmes, three studied in other university programmes. According to the interviewees, this heterogeneity was also the characteristic for the entire group of students.

5.1.2.1. Disciplinary competence. The heterogeneity of students had an impact on their perceptions of the development of disciplinary competencies. Table 5 lists the identified codes within the category 'Disciplinary competence' and maps them as disciplinary competencies ordered from the lower to the high cognitive level (Anderson and Krathwohl 2001) and the number of the interviewees of each category who mentioned to have these competencies at the end of the module. The students mentioned possessing the disciplinary competencies that corresponded to their prior knowledge. The students reported their confidence in programming knowledge and skills they had acquired and their ability to carry out future programming projects. It is worth noting that the beginners were willing to help other students complete programming assignments and carry out their own programming projects.

Table 4. Mean and standard deviation, results of the independent t -tests between the control and treatment groups in the module 'Programming' per factor with the alternative hypothesis that scores of the treatment group are higher (one-sided tail).

Factors	Control group		Treatment group		t	df	p	Cohens' d
	Mean	Std. dev.	Mean	Std. dev.				
Disciplinary competence	3.74	0.60	3.74	0.72	−0.023	94	0.491	0.005
Social competence	2.78	0.93	3.48	0.52	−4.748	89.46	0.000***	0.900
Systematic competence	3.10	0.98	3.64	0.63	−3.262	89.89	0.001**	0.639
Personal competence	3.29	1.13	3.41	0.86	−0.521	90	0.302	0.111
General competence	3.00	1.10	3.35	0.95	−1.582	89	0.059†	0.338
Motivation			3.59	0.81				
Learning process	3.52	0.84	3.54	0.67	−0.152	91.997	0.440	0.030

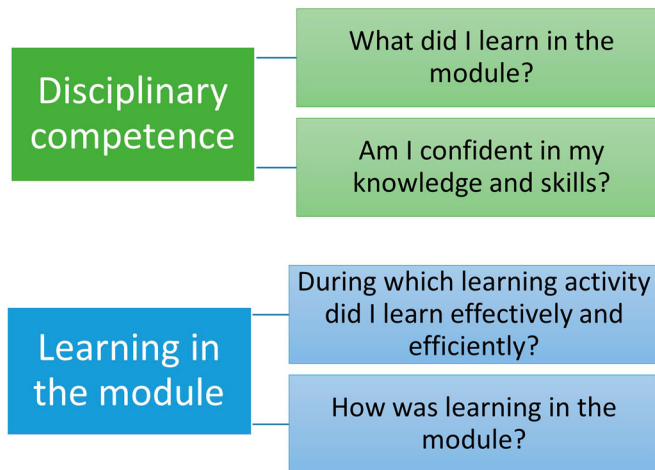


Figure 3. Analysis of students' interviews, broken in four categories.

Because of the different knowledge levels at the beginning of the module, the students perceived the improvement of their disciplinary competencies differently. While the beginners noticed that they learned a lot of programming, especially the application of basic and advanced topics, the students with programming experience said that they did not acquire additional disciplinary skills or deepen their knowledge. But they learned how to explain programming to others and manage complex programming projects, both on social and technical levels. This could be one reason why students did not, on average, perceive any improvement in disciplinary competencies.

Table 5. Codes of the category 'Disciplinary competence' which emerged in the student interviews.

Categories	Codes	Number of students by the prior knowledge categories (total 6 students)		
		1 (3 students)	2 (2 students)	3 (1 student)
What I learned in the module?	I know the basics of Java programming	3	2	1
	I know advanced Java programming topics	2	2	1
	I can write basic Java programs	3	2	1
	I can write advanced Java programs	1	2	1
	I can analyse someone else's Java program code	1	2	1
	I can evaluate Java program code	-	1	1
	I can perform complex Java programming projects in team	3	1	1
	I can perform complex Java programming projects	-	1	1
	I learned how to explain Java programming topics to other students	-	1	1
	I learned how to learn	1	1	1
Am I confident in my knowledge and skills?	I am confident in the basics of Java programming	3	2	1
	Confident in advanced Java programming topics	2	2	1
	I'm able to help other students in doing Java programming assignments or projects	2	1	1
	I am not confident in complex Java topics	1	-	-
	I am able to perform Java projects that require the knowledge and skills learned in the module	1	2	1
	I am able to perform Java projects that are in the area of my interest independent of their complexity	-	1	1

Notes: 1 = no prior programming knowledge; 2 = basic knowledge and little experience in a programming language other than Java; and 3 = intermediate knowledge and experience in Java and another programming language.

Other factors that negatively affected the students' perceptions were the complexity of learning activities and the workload in the module. The beginners noted some lab tasks and problems, especially at the end of the module, to be difficult. All interviewees found the project complex; however, depending on their prior programming knowledge, named different issues. While the beginners felt they were not prepared enough professionally to carry out the project, the students with basic programming backgrounds complained that the project requirements were not clearly defined, which took some effort to scale the project work and outcome. The student with the intermediate prior knowledge perceived the management of his heterogeneous project team difficult, but interesting and challenging. All the interviewed students reported a high workload in the module and found two projects (a trial and a main one) in the module too much.

5.1.2.2. Learning process in the module. Table 6 summarises categories and codes that explore how students perceived the learning in the module and how various aspects improved and hindered students' learning process.

5.2. Module 'Engineering of industrial cyber-physical systems'

Student self-perception surveys resulted in the sample sizes of 8 for the control group and 7 respondents for the treatment group with a response rate of 64% and 67%, respectively. A score for each factor of the questionnaire (see 4.2) was calculated based on the average of student responses to the questions assigned to this factor. Figure 4 shows the distributions of the control and treatment groups. Median and mean values of students' perception of improving their competencies are higher in the treatment group than in the control group for all factors (see also Table 7). The responses on all factors are less dispersed in the treatment than in the control group.

The effective differences within factors between the control and treatment groups were statistically assessed, effect sizes (Hedges' g) were estimated. Table 7 summarises this analysis along with the mean and standard deviation for each factor. The results show a significant increase due to the T-CHAT intervention on social ($p < .01$), personal ($p < .05$), disciplinary ($p < .1$) and general ($p < .1$) competence. Given the significance criterion (p -value $< .05$), desired statistical power (80%), anticipated difference in scores (effect size), and estimated measurement variability (standard deviation), the

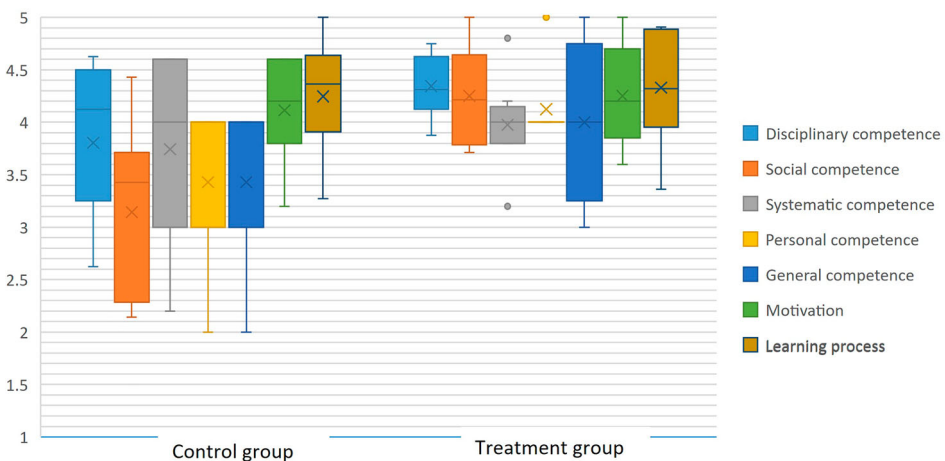


Figure 4. Box plot comparing the scores of control and treatment groups in the module 'Engineering of ICPS' per factor (mean value indicated by a cross). The 1.5 interquartile range (IQR) convention is used for the whiskers and the outlier identification.

Table 6. Codes of the category 'Learning in the module' which emerged in the student interviews.

Categories	Codes	Number of students by the prior knowledge categories (total 6 students)		
		1 (3 students)	2 (2 students)	3 (1 student)
During which learning activity did I learn effectively and efficiently?	Lectures	–	1	–
	Lab assignments and problem-solving	3	1	1
	Learning diary	–	1	–
	Research assignment	1	–	–
	Trial project	–	–	–
	Project	2	2	1
	Self-guided study	1	1	1
		<i>Students' perceptions</i>		
How was learning in the module?	Feedback of teacher on assignments	Two students of six mentioned that teacher's feedback on home assignments was not helpful		
	Students' own feedback	Five of six students mentioned that they were satisfied with how their feedback was implemented during the next teaching sessions		
	Freedom of how to implement code /solve problems	One student was fascinated by the freedom he has for learning and practicing: 'We were allowed to do whatever we wanted. I liked it because I love trying new things in practice'.		
	Writing a learning diary	All but one of the interviewed students claimed that writing a learning diary was ineffective and not useful for their learning and they did it because it was compulsory.		
	Trial project	All but one of the interviewed students found the trial project not useful for them. This one student said that this project helped him understand what teamwork means.		
	Project	All interviewed students said that this project was useful to understand how individual programming functionalities and techniques could be combined to work together towards a meaningful goal. Three students mentioned that the project was complex.		
	Complexity of assignments	The beginners (category 1) mentioned that programming tasks were complex, especially at the end of the module.		
	A considerable variety of learning activities	All interviewees emphasised that there were different types of learning activities that made learning difficult.		
	The workload in the module	Three students mentioned the high workload and effort involved in performing programming tasks. A student who had previously studied programming in another module found that the pace of learning was quite fast.		

Notes: 1 = no prior programming knowledge; 2 = basic knowledge and little experience in a programming language other than Java; and 3 = intermediate knowledge and experience in Java and another programming language.

required sample size must be between 24 and 53 in each group (McConnell, Monteiro, and Bryson 2019). Since both samples (the control and treatment groups) are significantly smaller and because *p*-values strongly depend on sample sizes, statistical significance of T-CHAT intervention cannot be shown for some factors (systematic competence and motivation).

Table 7. Mean and standard deviation, results of the independent *t*-tests between the control and treatment groups in the module ‘Engineering of ICPS’ per factor with the alternative hypothesis that scores of the treatment group are higher (one-sided tail).

Factors	Control group		Treatment group		<i>t</i>	df	<i>p</i>	Hedges’ <i>g</i>
	Mean	Std. dev.	Mean	Std. dev.				
Disciplinary competence	3.80	0.74	4.34	0.30	−1.812	7.783	0.054 †	0.929
Social competence	3.14	0.84	4.25	0.46	−3.241	13	0.003 **	1.579
Systematic competence	3.74	0.91	3.97	0.45	−0.611	8.448	0.279	0.311
Personal competence	3.43	0.79	4.13	0.35	−2.159	8.091	0.030 *	1.103
General competence	3.43	0.79	4.00	0.76	−1.433	13	0.088 †	0.698
Motivation	4.11	0.54	4.25	0.48	−0.518	13	0.307	0.252
Learning process	4.25	0.55	4.33	0.55	−0.291	13	0.388	0.142

The practical significance of the T-CHAT educational intervention indicates a large effect for the factors ‘Disciplinary’, ‘Social’, ‘Personal’, and ‘General’, and a medium effect for the ‘Systematic’ competence (Hattie 2008).

To better understand students’ perception of the development of systematic competence and their motivation during the T-CHAT intervention, two volunteer students (out of 8) were interviewed. One student emphasised that problem-solving activities in groups during F2F teaching empowered her to think critically and triggered the development of problem-solving skills. The other student reported that F2F teaching with peer activities guided him to successfully transfer new knowledge to the project work in this module and his own. Both students reported that their motivation to learn was fostered by the up-to-date practical relevance of the subject, the group activities that followed the presentation of theoretical content, and finally by the project work at the end of the module. They emphasised that they were well prepared for the project work through class activities and the self-guided analysis of industrial CPS of their interest.

6. Discussion and conclusions

Despite various curricula and modules introduced over the last few decades to teach cyber-physical systems (CPS) engineering, the competence gap, in technical and transferable competencies, persist between industry expectations and competencies of CPS graduates. The objective of this paper was to introduce the T-CHAT educational framework for teaching CPS engineering at the module level and to explore its effectiveness. This framework encompasses the T-CHAT learning process, which is aligned to learning phases and aims to develop professional knowledge and skills and to improve systematic, social and personal competencies of students. In contrast to the existing empirical studies, the current research compares the T-CHAT educational approach to an alternative teaching approach in two use cases by analysing quantitative and qualitative data of student perception.

In the ‘Programming’ module, the social, systematic, and general competencies of students statistically significantly improved with a large and medium treatment effect due to the use of the T-CHAT educational approach. Personal and general competencies improved on average, while the perception of the development of disciplinary competence remained on average at the same level. The latter can be explained by the high workload and the complexity of assignments that were emphasised in the student interviews.

In the ‘Engineering of Industrial Cyber-Physical Systems (ICPS)’ module, the use of the T-CHAT educational approach led to a statistically significant improvement in the majority of the factors – disciplinary, social, personal and general competencies – accompanied by a large treatment effect. Systematic competence and motivation improved on average in the treatment group. This statistically insignificant improvement can be explained by the small sample sizes of the control and treatment groups. In the interviews, the students emphasised the development of their critical thinking and problem-solving skills. The better results in the second module are because the

outcomes of the first module and reflection on using the T-CHAT approach informed its implementation and delivery.

A review of the standard deviation for the factors in the control and treatment groups in both modules provides an important insight into the impact of the T-CHAT educational approach on the development of the student competencies. For all factors except the disciplinary competence in the 'Programming' module, there is a reduction in the point estimate for standard deviation. That is a significant finding because it shows that the T-CHAT educational approach has led to a more homogeneous perception of learning outcomes of the entire group of students.

However, there are some differences in the results of both use cases. Compared to the first use case, the results in the second use case show the better values:

- the student answers are less dispersed,
- the majority of competencies have improved statistically significantly due to the T-CHAT educational intervention, and
- the practical significance has been proved by the significantly higher treatment effects.

The following questions arise, which are addressed directly in the following:

1. Which features of the modules and their delivery were the decisive for such differences?
2. What should be improved in the design and implementation of these modules so that they can better use the features of the T-CHAT approach?
3. How can the knowledge and experience gained in these two use cases be transferred to other modules and student cohorts?

6.1. Differences in the modules

Since the modules were implemented one year apart, the authors had a possibility to reflect on the results acquired in the 'Programming' module and adapt the use of the T-CHAT approach for the 'Engineering of ICPS' module. The main issue of the quantitative analysis in the 'Programming' module was that students in both control and treatment groups equally high perceived the development of their disciplinary competence. The authors explored the causes of this unexpected outcome in the student interviews and identified the following factors that could negatively affect the perception of students in the treatment group (see section 0):

- the complexity of assignments and project,
- a considerable variety of learning activities, and
- the workload in the module.

The majority of interviewees emphasised that, because of the high complexity of programming assignments, in particular at the end of the module, they were sometimes not able to solve them by themselves and had to invest a considerable effort and time for it. They also mentioned that the project task was difficult for the first-semester students. This high task complexity was perceived by the interviewed students as teacher's demanding expectations towards their disciplinary achievements in the module. According to Andrade and Du (2007), students who experience tension between their own and their teachers' expectations, especially if the last ones are demanding and novel, struggle to appropriate those expectations effectively. This incongruence and also the fact that the targets and skill level that students were meant to achieve in 'Programming' module were not exactly communicated to them, for instance, in the form of a rubric, made it for them difficult to objectively self-assess the development of the disciplinary competence (Andrade and Du 2007).

The interviewees found that learning activities in the module, including lab assignments, carrying out a research-based inquiry, project work and problem-solving sessions, were diverse and novel for them. They characterised some activities, for example, keeping a learning diary, as disruptive and inefficient for learning. To master this diversity successfully, students needed to be trained for this pedagogical change, particularly with regard to team work and management of real-life project (Winberg et al. 2020). Since this was not done prior to the T-CHAT intervention, the students perceived this diversity as an additional hurdle in learning the subject matter knowledge. This could negatively influence their perception of the development of disciplinary competence.

According to the interviewees, the task complexity and the variety of learning activities produced a high workload in the module. Demanding teachers' expectations and high workload express that teaching in this module was rigorous that could lead to underestimated student evaluations (Neal and Elliott 2009).

The authors took these disadvantages into account when implementing the T-CHAT educational approach in the 'Engineering of ICPS' module (see section 4.4.2). They directed the students' attention and effort to acquire the disciplinary knowledge and apply it to solving small tasks and problems, and then to a project. To give students more time to reflect on the acquired knowledge and the topics learned, they dispensed with research-based learning activities (RBL) and a learning diary, and reduced the number of assignments and problem-solving sessions compared to the 'Programming' module. As a result, the students experienced congruence with the teacher's expectations and perceived the improvement of their disciplinary competence compared to the control group (see Table 7).

The T-CHAT approach showed a medium to high practical effect for the factors in both use cases and in particular in the 'Engineering of ICPS' module (see Cohens' *d* in Table 4 and Hedges' *g* in Table 7). The identified practical effect on nearly all factors is higher in the 'Engineering of ICPS' module than in the 'Programming' module, except for the systematic competence. This can be explained by the fact that the teaching in the control group of the 'Programming' module partly included interactive methods and group activities, but in the 'Engineering of ICPS' module, technical knowledge was conveyed in classic frontal lectures without the students being involved in interactive learning. The lower effect size of the systematic competence in the 'Engineering of ICPS' module may be because no research-based learning activities took place and problem-based learning activities were shorter than in the 'Programming' module.

6.2. Possible improvements to the modules

The authors agree with Chonko, Tanner, and Davis (2002) that students should not be treated as customers who are entitled to success without hard work and effort and that good teaching does not mean doing only what students prefer. However, based on the results of surveys and interviews, there are some options to adapt teaching and make the learning more effective for students.

In the 'Programming' module, the main improvement would be the reduction of the module workload and providing more guidance in regard to learning activities. Instead of two real-life projects, only one project with unambiguously defined requirements has to be planned. This will focus student efforts on the targeted application of the disciplinary knowledge they had acquired in the lectures and problem-solving sessions. The number of planned learning activities, for instance, problem-solving sessions, should be reduced to give more time for a reflection on the learned material. Precise guidelines and instructions must be given for keeping a learning diary. Effective feedback on student solutions to programming tasks must be prompt.

In the 'Engineering of ICPS' module, a research-based learning activity, for instance, a literature-based inquiry, should be included in the T-CHAT learning process to trigger the development of personal and systematic competencies. This can be done through a reduction of the project work.

6.3. Transfer options

A statistically significant improvement of student competencies in two use cases due to the T-CHAT educational approach and a high practical significance supported by large treatment effects, in particular in the second use case, is an important result of this study that shows the effectiveness of this approach. The use and mix of the various educational approaches according to the T-CHAT learning process has a positive impact on the development of both disciplinary knowledge and the transferable skills of students.

This study creates an understanding of how the T-CHAT educational approach can be applied in other modules and student cohorts. A successful transition to the T-CHAT educational approach requires the preparation of both participants in the learning process – teachers and students. Analogous to the application of methods and approaches, the application of the T-CHAT educational approach requires that the teacher knows its philosophy, pedagogical methods, and how to apply them to their teaching practice. This requires faculty staff development and support, in particular, for the pedagogical methods other than classic frontal lectures that trigger the development of key competencies in students (Winberg et al. 2020).

To prepare students to participate in learning efficiently, the teacher has to ensure that the students know the targets they need to achieve and get an overview of the forthcoming learning activities. If the students were not prepared for project/problem/research-based learning activities in previous dedicated courses, a brief introduction to these approaches would be an advantage. The study showed that to successfully participate in the learning activities, the first-year students needed more extensive explanation and preparation compared to the master's students.

The T-CHAT approach begins with the module design in which the teacher first analyses the intended learning outcomes and determines the pedagogical approaches and learning activities to be used based on the mapping between the competencies and the pedagogical approaches in Table A3. The learning process can be designed based on the description in Section 3.1. The definition of problems, a project and a research task, must address the module learning outcomes and be tailored to the level of experience and maturity of the students. For instance, if interdisciplinary skills have to be trained, then the project task must be designed in an interdisciplinary manner. The level of autonomy given to students in project-based learning must be different for first-year and master' students (regarding autonomy levels, see De Graaff and Kolmos 2003).

6.4. Study limitations

The limitation of this study is the small sample sizes, in particular, in the second use case with master's students, and the limited number of use cases explored.

6.5. Future works

To obtain more evidence for the T-CHAT framework, future studies are planned to expand to more participating students in the existing T-CHAT modules (see 4.4). Other modules are planned to implement using the T-CHAT educational approach.

Although the T-CHAT approach has been introduced and used to improve the teaching of CPS engineering at the module level, it can also be applied at the curriculum level. For this purpose, curriculum leaders can use the list of competencies required of CPS engineering graduates (Table A1) to determine which competencies are to be developed in the module of the curriculum. Based on the mapping of competencies to educational approaches (Table A3), they can then specify which approaches will be used in the individual module. Finally, based on the T-CHAT learning process, teachers design their modules and use the prescribed educational approaches. Such an investigation and implementation of T-CHAT at the curriculum level is the subject of future research.

Acknowledgements

The authors thank Prof. Dr. Juho Mäkiö, the University of Applied Sciences Emden-Leer, Germany, for his helpful discussions and support.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Elena Mäkiö is a PhD student whose research focuses on holistic educational approaches for teaching cyber-physical systems engineering. She is Associate Fellow at Higher Education Academy, UK. She studied applied mathematics and worked as a software engineer of distributed safety-critical systems. She is currently working at the University of Emden/Leer, Germany, on a project that deals with the development of critical thinking in students.

Freeha Azmat is Associate Professor at WMG and is involved in different outreach programs related to augmented and virtual reality in education. She leads several modules related to Programming and Electronics in Applied Engineering Program and Dyson Engineering Degree Apprenticeship program. She led the design and development of a new Degree Apprenticeship in 'Digital Technology Solutions' and currently working as its Course Director. Her subject research interests are cognitive radio and the application of machine learning in wireless communication. Her Pedagogy research is about transforming traditional classroom teaching using Technology Enhanced Learning methods.

Bilal Ahmad is Associate Professor of the Automation Systems Group at WMG. The main focus of his work is on developing digital engineering tools and methods for lifecycle engineering of manufacturing automation systems (i.e. design, deployment, operation and maintenance), which are the key components in supporting modern engineering processes and organisations. His research interests are Automation Systems, Manufacturing Digitalisation, and Cyber Physical Systems.

Robert Harrison is a Professor of the Automation Systems Group at WMG. His research interests are manufacturing automation from business, technical and social perspectives, virtual engineering tools and related engineering services, particularly within the automotive and aerospace sectors. Professor Harrison is the author of around 150 peer-reviewed international journal and conference papers and gives frequent national and international presentations in academic and commercial contexts.

Armando Walter Colombo is a Professor of Electrotechnical and Industrial Informatics at the University of Applied Sciences Emden-Leer, Germany. He has extensive experience in managing multi-cultural research teams in multi-regional projects and has participated in leading positions in many international research and innovation projects related to Industrial Informatics. His research interests are in the fields of industrial cyber-physical systems, industrial digitalisation and system-of-systems engineering, Internet-of-Services, Industry 4.0-compliant solutions.

Ethical approval

Ethical approach was given by the Biomedical and Scientific Research Ethics Committee, Kirby Corner Road, Coventry CV4 8UW. Ethical Application Reference: BSREC-2019-2351 AM01.

References

- Aditomo, A., P. Goodyear, A.-M. Bliuc, and R. A. Ellis. 2013. "Inquiry-Based Learning in Higher Education: Principal Forms, Educational Objectives, and Disciplinary Variations." *Studies in Higher Education* 38 (9): 1239–1258.
- Anderson, G., and N. Arsenault. 2005. *Fundamentals of Educational Research*. 2nd ed. London: Falmer.
- Anderson, L. W., and D. R. Krathwohl. 2001. *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*, Abridged ed. New York: Longman.
- Andrade, H., and Y. Du. 2007. "Student Responses to Criteria-Referenced Self-Assessment." *Assessment & Evaluation in Higher Education* 32 (2): 159–181.
- Arana-Arexolaleiba, N., and M. I. Zubizarreta. 2017. "PBL Experience in Engineering School of Mondragon University." In *PBL in Engineering Education*, edited by Aida Guerra, Ronald Ulseth, and Anette Kolmos, 89–102. Sense Publishers.
- Atkins, E. M., and J. M. Bradley. 2013. "Aerospace Cyber-Physical Systems Education." *AIAA Infotech@ Aerospace (I@A) Conference*, 4809.
- Ausubel, D. P. 1963. *The Psychology of Meaningful Verbal Learning*. New York, NY: Grune & Stratton.

- Barnett, R. 1994. *The Limits of Competence: Knowledge, Higher Education and Society*. Buckingham: Open University Press.
- Barrows, H. S., and R. M. Tamblyn. 1980. *Problem-Based Learning: An Approach to Medical Education*. New York: Springer Publishing Company.
- Bauer, K., and K. Schneider. (2013). "Teaching Cyber-Physical Systems: A Programming Approach." *Proceedings of the Workshop on Embedded and Cyber-Physical Systems Education, WESE '12*, 3:1–3:8. Tampere, Finland: ACM. doi:10.1145/2530544.2530547.
- Bertels, P., M. D'Haene, T. Degryse, and D. Stroobandt. 2009. "Teaching Skills and Concepts for Embedded Systems Design." *ACM SIGBED Review* 6 (1): 1–8. doi:10.1145/1534480.1534484.
- Cancila, D., V. Nuzzo, M. Stoycheva, W. Birk, F. Asplund, and M. Torngren. 2016. "Experiences and Reflections on Three Years of CPS Summer Schools Within EIT Digital." *Proceedings of the 2016 Workshop on Embedded and Cyber-Physical Systems Education, WESE '16*, 7:1–7:4. Pittsburgh: ACM. doi:10.1145/3005329.3005336.
- Chen, H., K. Damevski, and W. M. Edwards. 2013. "Infusing Cyber-Physical Systems Concepts into an Introductory Computer Science Course." *Journal of Computing Sciences in Colleges* 28 (6): 26–34.
- Cheng, A. M. K. 2014. "An Undergraduate Cyber-Physical Systems Course." *Proceedings of the 4th ACM SIGBED International Workshop on Design, Modeling, and Evaluation of Cyber-Physical Systems, CyPhy '14*, 31–34. Berlin: ACM. doi:10.1145/2593458.2593464.
- Chonko, L. B., J. F. Tanner, and R. Davis. 2002. "What are They Thinking? Students Expectations and Self-Assessments." *Journal of Education for Business* 77 (5): 271–281.
- Colombo, A. W., G. J. Veltink, J. Roa, and M. L. Caliusco. 2020. "Learning Industrial Cyber-Physical Systems and Industry 4.0-Compliant Solutions." 2020 *IEEE Conference on Industrial Cyberphysical Systems (ICPS)* (Vol. 1, 384–390). IEEE. doi:10.1109/ICPS48405.2020.9274738.
- Crenshaw, T. L. A. 2013. "Using Robots and Contract Learning to Teach Cyber-Physical Systems to Undergraduates." *IEEE Transactions on Education* 56 (1): 116–120.
- Creswell, J. W.. 2009. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. London: Sage publications.
- CyPhERS. 2015. *CyPhERS FP7 Support Action* (Contract number 611430). <http://www.cyphers.eu/project/deliverables>.
- Damevski, K., B. Altayeb, H. Chen, and D. Walter. 2013. "Teaching Cyber-Physical Systems to Computer Scientists via Modeling and Verification." *Proceeding of the 44th ACM Technical Symposium on Computer Science Education, SIGCSE '13*, 567–572. Denver, CO: ACM. doi:10.1145/2445196.2445365.
- Deakins, E. 2009. "Helping Students Value Cultural Diversity Through Research-Based Teaching." *Higher Education Research & Development* 28 (2): 209–226.
- DECOS. 2007. "DECOS (Dependable Embedded Components and Systems), 2004–2007, EU-Call FP6-2003-IST-2, Contract n 511764." www.decos.at.
- De Graaff, E., and A. Kolmos. 2003. "Characteristics of Problem-Based Learning." *International Journal of Engineering Education* 19 (5): 657–662.
- Denzin, N. K., and Y. S. Lincoln. 2017. *The Sage Handbook of Qualitative Research*. London: Sage.
- De Winter, J., and D. Dodou. 2010. "Five-Point Likert Items: t Test Versus Mann-Whitney-Wilcoxon (Addendum Added October 2012)." *Practical Assessment, Research, and Evaluation* 15 (1): 11.
- Dochy, F., M. Segers, P. Van den Bossche, and D. Gijbels. 2003. "Effects of Problem-Based Learning: A Meta-Analysis." *Learning and Instruction* 13 (5): 533–568.
- English, M. C., and A. Kitsantas. 2013. "Supporting Student Self-Regulated Learning in Problem- and Project-Based Learning." *Interdisciplinary Journal of Problem-Based Learning* 7 (2): 128–150.
- Felder, R. M., R. Brent, and M. J. Prince. 2014. "Engineering Instructional Development: Programs, Best Practices, and Recommendations." In *Cambridge Handbook of Engineering Education Research*, edited by A. Johri and B. M. E. Olds, 409–436. Cambridge: Cambridge University Press.
- González, I., and A. Calderón. 2018. "Development of Final Projects in Engineering Degrees Around an Industry 4.0-Oriented Flexible Manufacturing System: Preliminary Outcomes and Some Initial Considerations." *Education Sciences* 8 (4): 214.
- Grega, W., and A. J. Kornecki. 2015. "Real-Time Cyber-Physical Systems Transatlantic Engineering Curricula Framework." 2015 *Federated Conference on Computer Science and Information Systems (FedCSIS)*, 755–762. doi:10.15439/2015F45.
- Hattie, J. 2008. *Visible Learning: A Synthesis of Over 800 Meta-Analyses Relating to Achievement*. London: Routledge.
- Healey, M., and A. Jenkins. 2009. *Developing Undergraduate Research and Inquiry*. Heslington, York: Higher Education Academy.
- Helps, R. G., and S. J. Pack. 2013. "Cyber-Physical System Concepts for IT Students." *Proceedings of the 14th Annual ACM SIGITE Conference on Information Technology Education*, 7–12.
- Henshaw, M., and L. Deka. 2018. "Transportation Cyber-Physical System as a Specialised Education Stream." In *Transportation Cyber-Physical Systems*, edited by L. Deka and M. Chowdhury, 227–246. Amsterdam: Elsevier.
- Ikonen, A., A. Piironen, K. Saurén, and P. Lankinen. 2009. "CDIO Concept in Challenge Based Learning." *Proceedings of the 2009 Workshop on Embedded Systems Education*, 27–32.
- Johnson, B., and R. Ulseth. 2017. "Iron Range Engineering Model." In *PBL in Engineering Education*, edited by Aida Guerra, Ronald Ulseth, and Anette Kolmos, 53–69. Leiden, Nederlande: Sense Publishers.

- Kadmon, M., V. Strittmatter-Haubold, R. Greifeneder, F. Ehlail, and M. Lammerding-Köppel. 2008. "Das Sandwich-Prinzip—Einführung in Lerner Zentrierte Lehr-Lernmethoden in der Medizin." *Zeitschrift Fuer Evidenz, Fortbildung und Qualitaet im Gesundheitswesen* 102 (10): 628–633.
- Kallia, M., and S. Sentance. 2017. "Computing Teachers' Perspectives on Threshold Concepts: Functions and Procedural Abstraction." *Proceedings of the 12th Workshop on Primary and Secondary Computing Education*, 15–24. ACM.
- Kim, Y., A. Chen, S. Jadhav, C. S. Gloster, T. Le, and P. Hsu. 2016. "Project Based Courses in Control Cyber Physical System co-Design." *Proceedings of the 2016 Workshop on Embedded and Cyber-Physical Systems Education*, 1–4.
- Kirschner, P. A., J. Sweller, and R. E. Clark. 2006. "Why Minimal Guidance During Instruction Does not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching." *Educational Psychologist* 41 (2): 75–86.
- Knetsch, M. L., and T. J. Cleij. 2017. "The Maastricht Science Programme: From Problem-Based Learning to Research-Based Learning in the Sciences." In *Research-Based Learning: Case Studies from Maastricht University*, edited by Ellen Basiaens, Jonathan van Tilburg, and Jeroen van Merrienboer, 121–134. Springer.
- Kolmos, A. 1996. "Reflections on Project Work and Problem-Based Learning." *European Journal of Engineering Education* 21 (2): 141–148.
- Kolmos, A., F. K. Fink, and L. Krogh. 2004. "The Aalborg Model-Problem-Based and Project-Organized Learning." *The Aalborg PBL Model-Progress, Diversity and Challenges*, 9–18. Aalborg University Press.
- Kolmos, A., and E. de Graaff. 2014. "Problem-Based and Project-Based Learning in Engineering Education." In *Cambridge Handbook of Engineering Education Research*, edited by A. Johri and B. M. Olds, 184–208. Cambridge: Cambridge University Press.
- Kolmos, A., J. E. Holgaard, and N. R. Clausen. 2021. "Progression of Student Self-Assessed Learning Outcomes in Systemic PBL." *European Journal of Engineering Education* 46 (1): 67–89.
- Kurki-Suonio, K. 2011. "Principles Supporting the Perceptual Teaching of Physics: A "Practical Teaching Philosophy?" *Science & Education* 20 (3-4): 211–243.
- Laird, L. 2016. "Strengthening the "Engineering" in Software Engineering Education: A Software Engineering Bachelor of Engineering Program for the 21st Century." *2016 IEEE 29th International Conference on Software Engineering Education and Training (CSEET)*, 128–131. doi:10.1109/CSEET.2016.13.
- Lawlor, O., S. Bogosyan, Y. Vural, I. Thompson, M. Moss, and M. Gokasan. 2015. "AERO-Beam: An Open-Architecture Test-bed for Research and Education in Cyber-Physical Systems." *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*, 5080–5086. IEEE.
- Lee, E. A., S. A. Seshia, and J. C. Jensen. 2013. "Teaching Embedded Systems the Berkeley Way." *Proceedings of the Workshop on Embedded and Cyber-Physical Systems Education, WESE '12*, 1:1–1:8. Tampere: ACM. doi:10.1145/2530544.2530545.
- Leitão, P., L. Ribeiro, J. Barata, and B. Vogel-Heuser. 2016. "Summer School on Intelligent Agents in Automation: Hands-on Educational Experience on Deploying Industrial Agents." *IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society*, 6602–6607. IEEE.
- Lieu Tran, T. B. Törnngren, M. Nguyen, H. D. Paulen, R. Gleason, N. W., and T. H. Duong. 2019. "Trends in Preparing Cyber-Physical Systems Engineers." *Cyber-Physical Systems* 5 (2): 65–91.
- Lima, R. M., J. Dinis-Carvalho, R. M. Sousa, A. C. Alves, F. Moreira, S. Fernandes, and D. Mesquita. 2017. "Ten Years of Project-Based Learning (PBL) in Industrial Engineering and Management at the University of Minho." In *PBL in Engineering Education*, edited by A. Guerra, R. Ulseth, and A. Kolmos, 33–51. Leiden, Niederlande: Sense Publishers.
- Mäkiö-Marusik, E. 2017. "Current Trends in Teaching Cyber Physical Systems Engineering: A Literature Review." *Industrial Informatics (INDIN)*, 2017 IEEE 15th International Conference on, 518–525. IEEE.
- Mäkiö-Marusik, E., B. Ahmad, R. Harrison, J. Mäkiö, and A. W. Colombo. 2018. "Competences of Cyber Physical Systems Engineers—Survey Results." *2018 IEEE Industrial Cyber-Physical Systems (ICPS)*, 491–496. IEEE.
- Mäkiö-Marusik, E., F. Azmat, B. Ahmad, R. Harrison, and W. A. Colombo. 2019. "Evaluation Instrument for Engineering Modules and Courses." *2019 IEEE 17th International Conference on Industrial Informatics (INDIN)*. IEEE.
- Mäkiö, J., E. Mäkiö-Marusik, and E. Yablochnikov. 2016. "Task-Centric Holistic Agile Approach on Teaching Cyber Physical Systems Engineering." *Industrial Electronics Society, IECON 2016-42nd Annual Conference of the IEEE*, 6608–6614. IEEE.
- Mäkiö, E., J. Mäkiö, A. W. Colombo, R. Harrison, B. Ahmad, and F. Azmat. 2020. "Work in Progress: Task-Centric Holistic Teaching Approach to Teaching Programming with Java." *2020 IEEE global Engineering Education Conference (EDUCON)*, 1487–1492. IEEE.
- Marwedel, P., and M. Engel. 2014. "Flipped Classroom Teaching for a Cyber-Physical System Course—an Adequate Presence-Based Learning Approach in the Internet age." *Microelectronics Education (EWME), 10th European Workshop on*, 11–15. IEEE.
- McConnell, M. M., S. Monteiro, and G. L. Bryson. 2019. "Sample Size Calculations for Educational Interventions: Principles and Methods." *Canadian Journal of Anesthesia/Journal Canadien D'anesthésie* 66 (8): 864–873.
- Meyer, J., and R. Land. 2003. *Threshold Concepts and Troublesome Knowledge: Linkages to Ways of Thinking and Practising Within the Disciplines*. Edinburgh: University of Edinburgh .
- Mills, J. E., and D. F. Treagust. 2003. "Engineering Education – is Problem-Based or Project-Based Learning the Answer." *Australasian Journal of Engineering Education* 3 (2): 2–16.

- National Academies of Sciences. 2015. *Interim Report on 21st Century Cyber-Physical Systems Education*. Washington, DC: The National Academies Press. doi:10.17226/21762.
- National Academies of Sciences. 2016. *A 21st Century Cyber-Physical Systems Education*. Washington, DC: The National Academies Press. doi:10.17226/23686.
- Neal, C. S., and T. Elliott. 2009. "The Ethics of Setting Course Expectations to Manipulate Student Evaluations of Teaching Effectiveness in Higher Education: An Examination of the Ethical Dilemmas Created by the Use of SETEs and a Proposal for Further Study and Analysis." *Contemporary Issues In Education Research* 2 (3): 7–10.
- Neuman, W. L. 2014. *Basics of Social Research: Qualitative & Quantitative Approaches*. USA: Pearson Education Limited.
- Orth, H. 1999. *Schlüsselqualifikationen an Deutschen Hochschulen: Konzepte, Standpunkte und Perspektiven*. Darmstadt: Hermann Luchterhand Verlag.
- Pechmann, A., J. Wermann, A. W. Colombo, and M. Zarte. 2019. "Using a Semi-Automated job-Shop Production System Model to Prepare Students for the Challenges of Industrial Cyber-Physical Systems." *Procedia Manufacturing* 31: 377–383.
- Peter, S., F. Momtaz, and T. Givargis. 2015. "From the Browser to the Remote Physical lab: Programming Cyber-Physical Systems." *2015 IEEE Frontiers in Education Conference (FIE)*, 1–7. IEEE.
- Plateaux, R., O. Penas, J. Y. Choley, F. Mhenni, M. Hammadi, and F. Louni. 2016. "Evolution from Mechatronics to Cyber Physical Systems: An Educational Point of View." *2016 11th France-Japan 9th Europe-Asia Congress on Mechatronics (MECATRONICS) /17th International Conference on Research and Education in Mechatronics (REM)*, 360–366. doi:10.1109/MECATRONICS.2016.7547169.
- Race, P. 2014. *The Lecturer's Toolkit: A Practical Guide to Assessment, Learning and Teaching*. London: Routledge.
- Salewski, F., and R. Schmidt. 2015. "Teaching Industrial Automation: An Approach for a Practical Lab Course." *Proceedings of the WESE'15: Workshop on Embedded and Cyber-Physical Systems Education, WESE'15*, 1:1–1:7. Amsterdam: ACM. doi:10.1145/2832920.2832921.
- Schoitsch, E. 2014. "Introduction to Special Sessions TET-DEC I and II: Teaching, Education and Training Viewed from European Projects' Perspectives." *2014 40th EUROMICRO Conference on Software Engineering and Advanced Applications*, 408–416. doi:10.1109/SEAA.2014.86.
- Shadish, W. R., and J. K. Luellen. 2006. "Quasi-Experimental Design." In *Handbook of Complementary Methods in Education Research*, edited by J.L. Green, G. Camilli, and P.B. Elmore, 539–550. Abingdon: Routledge.
- Simons, S., P. Abé, and S. Naser. 2017. "Learning in the AutFab—the Fully Automated Industrie 4.0 Learning Factory of the University of Applied Sciences Darmstadt." *Procedia Manufacturing* 9: 81–88.
- Tabachnick, B. G., and L. S. Fidell. 2007. *Using Multivariate Statistics*. New York: Allyn & Bacon/Pearson Education.
- Taha, W., L.-G. Hedstrom, F. Xu, A. Duracz, F. A. Bartha, Y. Zeng, J. David, et al. 2016. "Flipping a First Course on Cyber-Physical Systems: An Experience Report." *Proceedings of the 2016 Workshop on Embedded and Cyber-Physical Systems Education, WESE '16*, 8:1–8:8. Pittsburgh, PA: ACM. doi:10.1145/3005329.3005337.
- Taha, W., Y. Zeng, A. Duracz, X. Fei, K. Atkinson, P. Brauner, R. Cartwright, et al. 2017. "Developing a First Course on Cyber-Physical Systems." *ACM SIGBED Review* 14 (1): 44–52. doi:10.1145/3036686.3036692.
- Thiede, S., M. Juraschek, and C. Herrmann. 2016. "Implementing Cyber-Physical Production Systems in Learning Factories." *Procedia CIRP* 54: 7–12. doi:10.1016/j.procir.2016.04.098.
- Thomas, D. R. 2006. "A General Inductive Approach for Analyzing Qualitative Evaluation Data." *American Journal of Evaluation* 27 (2): 237–246.
- Törngren, M., S. Bensalem, J. McDermid, R. Passerone, A. Sangiovanni-Vincentelli, and B. Schätz. 2015. "Education and Training Challenges in the Era of Cyber-Physical Systems: Beyond Traditional Engineering." *Proceedings of the WESE'15: Workshop on Embedded and Cyber-Physical Systems Education, WESE'15*, 8:1–8:5. Amsterdam: ACM. doi:10.1145/2832920.2832928.
- University of Emden/Leer, Germany. n.d. "Master in Industrial Informatics – Specialization Industrial Cyber-Physical Systems." <https://www.daad.de/deutschland/studienangebote/international-programmes/en/detail/4775/>.
- Verbic, G., C. Keerthisinghe, and A. C. Chapman. 2017. "A Project-Based Cooperative Approach to Teaching Sustainable Energy Systems." *IEEE Transactions on Education* 60 (3): 221–228. <http://0-search.ebscohost.com/pugwash.lib.warwick.ac.uk/login.aspx%3fdirect%3dtrue%26db%3dtrh%26AN%3d124539441%26site%3dedds-live&group=trial>.
- Veza, I., N. Gjeldum, and M. Mladineo. 2015. "Lean Learning Factory at FESB—University of Split." *Procedia Cirp* 32: 132–137.
- Vygotsky, L. S. 1978. *Mind in Society*. Cambridge, MA: Harvard University Press.
- Wade, J., R. Cohen, M. Blackburn, E. Hole, and N. Bowen. 2015. "Systems Engineering of Cyber-Physical Systems Education Program." *Proceedings of the WESE'15: Workshop on Embedded and Cyber-Physical Systems Education, WESE'15*, 7:1–7:8. Amsterdam: ACM. doi:10.1145/2832920.2832927.
- Wermann, J., N. Kliesing, A. W. Colombo, and E. C. Moraes. 2015. "Impact of New ICT Trends for the Educational Curriculum in the Area of Industrial Automation and Engineering." *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*, 3643–3648. IEEE. doi:10.1109/IECON.2015.7392667.
- Westwood, P. S. 2008. *What Teachers Need to Know About Teaching Methods*. Australia: ACER Press.
- Winberg, C., M. Bramhall, D. Greenfield, P. Johnson, P. Rowlett, O. Lewis, J. Waldoock, et al. 2020. "Developing Employability in Engineering Education: a Systematic Review of the Literature." *European Journal of Engineering Education* 45 (2): 165–180.

Appendix

Table A1. Required competencies of CPS engineering graduates.

Competencies of CPS engineering graduates		
Disciplinary Competencies	General (TG)	A holistic, broad view of CPS to be engineered (TG-1) Sound knowledge of disciplinary fundamentals. Theoretical understanding. (TG-2) Critical awareness of the multidisciplinary context of engineering (TG-3) Higher-order cognitive skills (TG-4) Engineering practice and application of knowledge (TG-5)
	CPS Foundations (TF)	Computing concepts, computer science, SW Engineering (TF-1) Computing for the physical world: sensors, actuators, embedded systems (TF-2) Discrete and continuous mathematics (TF-3) Cross-cutting application of sensing, actuation, control, communication, and computing (TF-4) Modelling of heterogeneous and dynamic systems integrating control, computing, and communication (TF-5) CPS development life cycle: requirements, concept, model-based design, simulation, formal verification and validation, testing, manufacturing, deployment and sustainment (TF-6)
	Non-functional characteristics of CPS (TNF)	Security and privacy (TNF-1) Interoperability (TNF-2) Reliability and dependability (TNF-3) Power and energy management (TNF-4) Safety (TNF-5) Stability and performance (TNF-6) Human factors and usability (TNF-7)
	Engineering (TE)	Engineering Process (TE-1) Industrial automation, plant modelling (TE-2)
	Systems Engineering (TSE)	System-level approach (TSE-1) Systems integration across domains (TSE-2) Systems of Systems (TSE-3)
	Others (TO)	Statistical methods and mining techniques (TO-1) Physics (TO-2)
Key (generic) competencies	Social Competence (SoC)	Collaboration (especially in heterogeneous interdisciplinary multicultural teams); collaboration with customers (SoC-1) Communication (especially within heterogeneous interdisciplinary multicultural teams and with customers) (SoC-2) Technical writing (SoC-3) Presentation (SoC-4)
	Personal competence (PC)	Creativity (PC-1) Entrepreneurship, successful transferring plans into reality (PC-2) Flexibility to manage rapidly evolving technologies (PC-3) Leadership (PC-4) Lifelong learning (PC-5) Innovation (PC-6) Working and thinking independently (PC-7) Taking responsibility and making decisions (PC-8)
	Systematic competence (SC)	Analytical skills (SC-1) Critical thinking and critical attitude (SC-2) Definition and solving problems (SC-3) Cross-disciplinary thinking (SC-4) Interdisciplinary thinking (SC-5)
	General competence (GC)	Project management (GC-1) Business and management (GC-2) Cultural and social awareness (GC-3) Humanities (e.g. anthropology, sociology) (GC-4) Legislation (GC-5)

Table A2. Gaps in the qualification of CPS engineers.

Gaps in the qualification of CPS engineers		
Disciplinary Competencies	General (TG)	Broad knowledge and skills of multiple areas of engineering expertise Broad system perspective. Understanding of the complete heterogeneous systems
	CPS Foundations (TF)	Hands-on experience in system/product development process Computer science. Digital/software technology Mathematics/mathematics frameworks Integration of Embedded systems, human element and networking Modelling, architecting and analysis of heterogeneous and dynamic systems, integrating control, computing and communication Systems analysis using formal methods and model-based verification Design theory. Cross-disciplinary design
	Non-functional characteristics of CPS (TNF)	Security and privacy Dependability issues Human factors and usability Risk and safety analysis
	Systems Engineering (TSE)	Systems-level thinking – abstraction and system interaction System integration and composition
	Others (TO)	Physics
	Social Competence (SoC)	Collaboration (especially in heterogeneous interdisciplinary multicultural teams); collaboration with customers Communication (especially within heterogeneous interdisciplinary multicultural teams and with customers) Presentation
	Personal competence (PC)	Creativity Entrepreneurship, successful transferring plans into reality Lifelong learning Critical thinking and critical attitude towards technological developments Cross-disciplinary thinking
	Systematic competence (SC)	Critical thinking and critical attitude towards technological developments Cross-disciplinary thinking
	General competence (GC)	Project management
Key (generic) competencies		

Table A3. Competencies of CPS engineering graduates and pedagogical approaches that can promote their development PjBL – project-based learning, PBL – problem-based learning, RBL – research-based learning, F2F – face-to-face teaching.

Competencies of CPS engineers			PjBL	PBL	RBL	F2F
Disciplinary Competencies	General (TG)	A holistic, broad view of CPS to be engineered (TG-1)				
		Sound knowledge of disciplinary fundamentals.			X	X
		Theoretical understanding (TG-2)				
		Critical awareness of the multidisciplinary context of engineering (TG-3)	X	X		X
		Higher-order cognitive skills (TG-4)	X	X	X	X*
Key competencies	Social Competence (SoC)	Engineering practice and application of knowledge (TG-5)	X	X		
		Collaboration (especially in heterogeneous interdisciplinary multicultural teams); collaboration with customers (SoC-1)	X	X		
		Communication (especially within heterogeneous interdisciplinary multicultural teams and with customers) (SoC-2)	X	X		
		Technical writing (SoC-3)	X		X	
		Presentation (SoC-4)	X	X		X*
	Personal competence (PC)	Creativity (PC -1)			X	X*
		Entrepreneurship, successful transferring plans into reality (PC -2)	X			
		Flexibility to manage rapidly evolving technologies (PC -3)	X			
		Leadership (PC -4)	X	X		
		Lifelong learning (PC -5)		X	X	
		Innovation (PC -6)			X	
		Working and thinking independently (PC -7)			X	X
		Taking responsibility and making decisions (PC -8)	X	X	X	
	Systematic competence (SC)	Analytical skills (SC -1)	X	X	X	
		Critical thinking and critical attitude (SC -2)	X	X	X	
		Definition and solving problems (SC -3)		X	X	
		Cross-disciplinary thinking (SC -4)	X	X		
		Interdisciplinary thinking (SC -5)	X	X		
	General competence (GC)	Project management (GC-1)	X			
		Business and management (GC-2)	X			
		Cultural and social awareness (GC-3)	X	X		X*

* - valid for constructivist teaching approaches of F2F.

Evaluation instrument

Question ID	Statement	Competence to be assessed
<i>Disciplinary competence</i>		
Q1	Due to this module, I understand the basic definitions of the renewable energy systems.	Bloom's level 2 (Understand)
Q2	Due to this module, I understand the fundamental problems in the field of sustainable energy systems.	Bloom's level 2 (Understand)
Q3	Due to this module, I am able to choose the adequate methods to the problems of this field.	Bloom's level 3 (Apply)
Q4	I am able to use basic theoretical knowledge and practical skills in the subject.	Bloom's level 3 (Apply)
Q5	I am able to analyse solutions and processes of the subject.	Bloom's level 4 (Analyze)
Q6	I am able to argue and evaluate the given problems and solutions of the topic.	Bloom's level 5 (Evaluate)
Q7	I am able to compare and find significant connections and correlations in the field.	Bloom's level 5 (Evaluate)
Q8	I am able to formulate solutions using the methods, techniques and tools of the subject.	Bloom's level 6 (Create)

(Continued)

Continued.

Question ID	Statement	Competence to be assessed
<i>Social competence</i>		
Q9	Due to this module it is easier for me to express my own opinions.	Communication
Q10	Due to this module I make my verbal contributions in more comprehensible language.	Communication
Q11	Due to this module it is easier for me to ask when I have not understood something.	Communication
Q12	I participated in the work planning within the team during this module.	Collaboration
Q13	I contributed to the assignment of tasks within the team during this module.	Collaboration
Q14	Due to this module I can better hold a presentation.	Presentation
Q15	Due to this module I can better write technical texts.	Technical writing
<i>Systematic competence</i>		
Q16	Due to this module I can better critically question and evaluate new ideas/things.	Critical thinking
Q17	Due to this module I can better think across technical and non-technical considerations, can better see things from different perspectives.	Cross-disciplinary thinking
Q18	Due to this module I can work more systematically and logically, can better collect, visualize and analyse information.	Analytical skills
Q19	Due to this module I can better identify and develop new things at my workplace/in my own projects.	Successful transferring plans into reality, creativity
Q20	Due to this module I can better solve problems of different nature that I encounter at my workplace/in my own projects.	Problem-solving skills
<i>General competence</i>		
Q21	Due to this module I can better manage my future projects as well as projects at my workplace.	Project management
<i>Personal competence</i>		
Q22	Due to this module I can better find and apply information about methods, techniques and tools needed to solve an issue.	Lifelong learning, self-directed learning
<i>Learning process</i>		
Q23	The objectives are clear.	
Q24	The content is appropriate.	
Q25	The content is interesting.	
Q26	The information in this module is appropriate for me / my company/workplace.	
Q27	Staff are good at explaining things.	
Q28	Staff make the subject interesting.	
Q29	Staff are enthusiastic about what they taught.	
Q30	The module is intellectually stimulating.	
Q31	I am happy with the pace of learning.	
<i>Motivation</i>		
Q32	I am motivated to participate in this module.	
Q33	In this module I have been encouraged to develop my own learning skills.	
Q34	In this module the learning is easy.	
Q35	I feel satisfied with this module.	
Q36	I would recommend this module to other students.	

Questions of semi-structured interviews with students in "Programming" module.

Theme 1. What was your learning experience? Different teaching methods having different learning activities were used during the module, e.g. lecture, project work, solving small tasks/problems. If we look at two characteristics of learning: effective learning that means "learning what is aimed by the module" and efficient learning that means "learning what is aimed without wasting time or energy".

- When or during which learning activity did you learn efficiently?
- Which learning activities did you not find useful?
- Which learning activities best supported your learning?
- How often have you used the opportunity to ask open questions to lecturers? What do you think about the possibility of giving feedback at the end of each lecture?

Theme 2. What did you learn in this module?

- What did you learn in this module? Name the most important things you learned in this module.
- When you did the project work, did you feel that you were technically well prepared? If not, what was missing?
- Which key, or soft, competences have you developed during the module?
- Have your expectations been met?
- Do you believe that with the knowledge and experience gained in the module you will be able to implement software development projects in Java.

Theme 3. What was your motivation?

- Did you enjoy the work (e.g. project work)?
- Which learning activities have motivated you?
- Which learning activities have negatively influenced your motivation?

Theme 4. Overall impression

- What is the most important thing you took from the module?
- What would you change about the module?
- What was good about the module?
- What was challenging for you and what was easy for you?
- How do you feel at the end of the module?

Questions of semi-structured interviews with students in “Engineering of Industrial Cyber-Physical Systems” module

Theme 1. What was your learning experience?

- How many teaching sessions did you attend?
- When or during which learning activity did you learn efficiently?
- Which learning activities best supported your learning?
- What do you think about the online format of teaching?

Theme 2. What did you learn in this module?

- What did you learn in this module? Name the most important things you learned in this module.
- When you did the project work, did you feel that you were technically well prepared? If not, what was missing?
- How easily did you apply the acquired knowledge to your project?
- Have your expectations been met?

Theme 3. What was your motivation?

- How motivated were you in the sub-module?
- Which learning activities have motivated you?
- Which learning activities have negatively influenced your motivation?

Theme 4. Overall impression

- What would you change about the sub-module?
- What was good about the module?