Competences of Cyber Physical Systems Engineers – Survey Results

Elena Mäkiö-Marusik, Bilal Ahmad, Robert Harrison
Warwick Manufacturing Group (WMG)
University of Warwick
Coventry, UK
(E.Makio-Marusik, B.Ahmad, Robert.Harrison)@warwick.ac.uk

Juho Mäkiö, Armando Walter Colombo
Faculty of Technology
University of Applied Sciences Emden/Leer
Emden/Leer, Germany
(Juho.Maekioe, Armando.Colombo)@hs-emden-leer.de

***Abstract*— Cyber physical systems (CPS) consist of physical and cyber components seamlessly integrated with each other. Being a core and an essential component within the digitalization process, CPS are becoming pervasive in all spheres of modern society. Understanding CPS structures and associated functionalities requires a multidisciplinary body of knowledge and engineering capabilities. Moreover, they are laying on the edge of a broad spectrum of methodologies and technologies, from mechatronics, communication, control and automation to information technologies, which are penetrating each corner of the society. It is obvious from the lifecycle of CPS, i.e., life cycle of the physical-part and the digital thread of the cyber-part, that developers, operators and managers of CPS have to acquire an essential interdisciplinary engineering qualification and a combination of skills and competencies from many different disciplines, including social and psychological aspects, among others. In order to develop and implement an adequate educational programme, two major aspects have been analysed in this paper: (i) identification and understanding of the minimal set of multidisciplinary competencies and qualifications needed and (ii) identification and classification of the critical gaps in the existing engineering curricula. The analysis is based on the findings of a survey conducted in two IEEE conferences closely related to the engineering disciplines associated with CPS.**

Keywords—CPS; education of CPS engineering; teaching of CPS engineering; competences of CPS engineers; competence gaps; survey; survey results

I. Introduction

Cyber-physical systems (CPS) are digitally networked interacting systems that consist of a physical and a virtual part. The physical part represents real physical objects such as sensors, actuators and machine tools. The virtual part serves as a cyber image of the physical objects. CPS are part of the Internet of Things (IoT) and are the core elements of Industry 4.0 concept [1], the Industrial IoT (IIoT). CPS are applied, for instance, in industrial automation in smart factories, in electrical grids, health care, aerospace, agriculture, communication and other application areas characterised by the term “smart”.

Currently, the market of IoT is rapidly expanding and this trend will continue. For instance, “IoT investments by businesses is expected to grow from $215B in 2015 to $832B in 2020, while consumer spending on IoT solutions is expected to rise from $72B to $236B“ [2]. At the same time, “by 2020, 50% of IoT spending will be driven by discrete manufacturing, transportation, and logistics, and utilities” [2]. It is also predicted that “IoT will have the most transformative effect on industries that are not technology-based today” [2].

With continually growing IoT and IIoT markets the demand for engineers and experts being capable to develop, operate, maintain and manage CPS underlying the IoT and the IIoT is rapidly rising. CPS are software intensive smart systems that are networked and able to collaborate for achieving common objectives, to adapt themselves to their surrounding physical and cyber environments and to structurally evolve [3]. Systems that are built up of a large number of networked and autonomous CPS can show emergent behavior [4]. Consequently, development of such systems requires a wide range of knowledge and skills in multiple academic disciplines and thus presents a set of challenges for educators and students of engineering disciplines related to CPS.

Several research and governmental initiatives (cmp. [5], [6], [7], [8]) have been taken in the last years aiming to answer the questions:

- Which educational qualifications are requisite for CPS development?
- What are the gaps in the competences of today’s CPS workforce?

For instance, in studies [5], [6] some selected representatives of USA industry and academia shared their insights, ideas and experiences about the qualifications required for CSP engineers and the gaps in their existing competences. Study [7] presents results of workshops concerning teaching and education that ran in scope of European projects. In [8] the authors summarise results of an international workshop on Embedded and Cyber-Physical Systems Education. These and also other studies (cmp. [9], [10], [11], [12]) obtained insights into the required qualifications and existing competence gaps of CPS engineers mostly through some informal interviews and workshops with some selected representatives of academia and industry. However, the results are not presented in a systematic way.

The study performed by the authors aims to obtain a extended insight into the two questions mentioned above. For this purpose a questionnaire was developed and two surveys were conducted in two IEEE conferences INDIN’2017 [13] and IECON’2017 [14]. The findings of the survey are presented in this paper.

The rest of the paper is structured as follows: section II describes the background of the survey; section III discusses the questionnaire and survey results; finally section IV presents conclusions and outlines possible outlooks of the work done till now.

II. Background

To find out qualifications of CPS engineers required by industry and academia as well as existing competence gaps a Systematic Literature Review (SLR) was conducted and published in [15]. In the course of this SLR two key results were obtained that have a significant relevance to the current research.

Firstly, competences of CPS engineers were identified and classified. The competences were assigned to key categories: CPS foundations, non-functional characteristics of CPS, engineering, business and humanities, social knowledge and skills, and personal traits and attitudes. These categories were used in the questionnaire as predefined selection possibilities.

Secondly, 11 studies were identified dealing with requirements of industry and academia for CSP engineers. The requirements were mapped onto the identified competences. The basis of these studies was created by different kinds of research activities that caused differences in scope as well as varying degree of intensity and precision. Outcomes of a program started by National Academy of Engineering, [5] and [6], describe educational requirements and current efforts as well as strategies and programmes for development of CPS curricula. Studies [7] and [9] present the results in the area of education and teaching CPS of the ARTEMIS [10]/DECOS [11] and CyPhERS FP7 [12] projects respectively. Study [16] demonstrates the results of a literature review on competences required for Industry 4.0 while [17] presents results of a Swiss job market investigation and of interviews with experts. References [18], [19] and [8] provide an overview of educational needs in CPS area and discuss key issues in CPS curriculum design. Finally, [20] and [21] present results of their investigations in the area of multidisciplinary education and systems engineering for CPS respectively.

These studies reported a number of competences that CPS engineers need to have as well as a number of existing competence gaps. However, each paper considered only some aspects of the competences and gaps. Moreover, these competences and gaps are not prioritised on their significance. To address the limitation of the existing studies, a survey among a large number of specialists in the area of CPS will deliver more detailed comprehension of needs in qualifications of CPS engineers. The data delivered by such survey can be statistically analysed and presented in a structured and systematic way. Different perspectives and viewpoints on competences of CPS engineers can be investigated. Based on the results, precise recommendations for CSP education can be given. Conferences dealing with the topic of CPS offer a great opportunity to conduct such studies. The conference participants usually come both from academia and industry and have diverse backgrounds concerning research, teaching and engineering.

III. Survey Description and Evaluation of Results

This section describes the two conducted surveys, their frameworks and results. The first survey was carried out within IEEE 15th International Conference on Industrial Informatics INDIN in July 2017 [13]. The second survey was conducted in IECON 2017, the 43rd Annual Conference of the IEEE Industrial Electronics Society, in October 2017 [14]. These surveys aimed to investigate which qualifications of CPS engineers are considered important by the conference participants and which gaps in competences they currently recognise. A questionnaire was developed to support survey participants in formulation of their preferences.

A. *Questionnaire*

The questionnaire contained two groups of questions:

- questions regarding survey participant's background
- questions regarding the required skills and gaps

The questions about participant's background enquired about gender (male/ female), workplace (academia/ industry/ both), core responsibility (management/ engineering/ research), and years of experience in the field of CPS. The question regarding the required skills and gaps are given in Table I:

TABLE I. Survey questions regarding required skills and gaps

Question ID	Question
Q1	Select 7 most important competences CPS Engineers / CPS Engineering graduates need to have
Q2	Select 5 competence gaps of CPS Engineers / CPS Engineering graduates

For selection of competences and gaps, a table with pre-defined competences of CPS engineers was provided in the questionnaire that was based on the classification made in [15]. Therefore, respondents were partly guided in their answers by the provided list of the competences. The provided list of the competences, divided into categories, is presented in Table II.

TABLE II. Competences of CPS Engineers

Categories	Competences
CPS Foundations **(TF)**	Computer science/ SW Engineering **(TF-1)**
	Sensors, actuators, embedded systems **(TF-2)**
	Discrete and continuous mathematics **(TF-3)**
	Application of sensing, actuation, control, communication, and computing **(TF-4)**
	Modeling of heterogeneous and dynamic systems integrating control, computing, and communication **(TF-5)**
	CPS development life cycle **(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 modeling **(TE-2)**

	System-level approach **(TE-3)**
	Systems integration across domains **(TE-4)**
	Systems of Systems **(TE-5)**
Business & Humanities **(B)**	Project management **(B-1)**
	Economics **(B-2)**
	Humanities (e.g. anthropology, sociology) **(B-3)**
	Legislation **(B-4)**
Social Knowledge and Skills **(SC)**	Collaboration **(SC-1)**
	Communication **(SC-2)**
	Technical writing **(SC-3)**
	Presentation **(SC-4)**
Personal traits and attitudes **(A)**	Analytical skills **(A-1)**
	Creativity **(A-2)**
	Entrepreneurship, successful transferring plans into reality **(A-3)**
	Critical thinking and critical attitude towards technological developments **(A-4)**
	Cross-disciplinary thinking **(A-5)**
	Lifelong learning **(A-6)**

B. *Analysis of Survey Data*

The aim of data analysis was to find out which competences and gaps are, in statistical terms, the most important from the respondents' perspective. As some respondents' background information was also collected, the analysis of different perspectives and their comparison has been performed.

In both surveys 116 respondents took part: 22 females and 94 males. The average work experience of respondents in the field of CPS was about 5.3 years (minimum = 0, maximum = 35, median = 3.0, standard deviation = 5.7). First of all, the data were cleansed. From 116 survey forms 97 and 98 contained the required number of selections for questions Q1 and Q2 respectively. Those answer sheets that contained from 4 to 10 selections for question Q1 (15 forms) and from 3 to 7 selections for question Q2 (12 forms) were also analysed. Therefore, for data analysis of question Q1 112 forms and of question Q2 110 forms were taken.

For data analysis the total number of votes given by the respondents per question was taken as a basis. For question Q1 each respondent had 7 votes, whereas for question Q2 5 votes. Altogether, there were 779 votes given to competences for question Q1 and 537 votes given to the gaps for question Q2. To get comparable results of the both survey questions, the data have been normalised to the mean number of votes given per competence/gap, which was taken as 1.0.

C. *Demographics*

Most of the participants, i.e. 86%, came from academia, 9% participants were from industry, the rest 4% work both in academia and industry.

The respondents were allowed to name several areas of their core responsibility. Majority of the respondents (i.e. 79%) were engaged in research, 21% dealt with engineering and teaching, and 11% represent management (see Fig. 1).

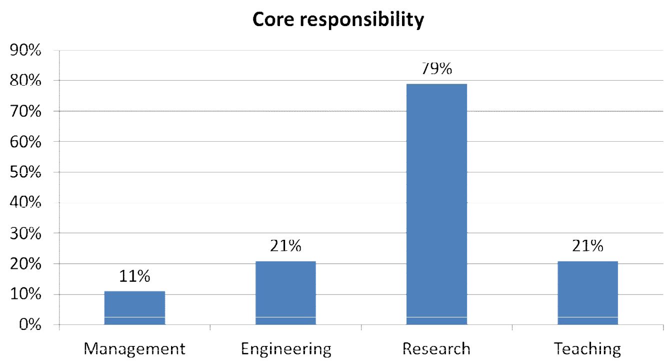

Fig. 1. Respondents' core responsibility

D. *Results of question **Q1** - Competences of CPS Engineers*

Question Q1 was aimed to find out which competences of CPS engineers were most important for the respondents. Figure 2 shows the top seven competences of CPS engineers with the percentage of respondents who chose them important. It can be seen that three competences of category "CPS Foundations" are part of the top seven. Competence "**TF-1** Computer science/ SW Engineering" is the most significant. It is interesting to note that "**SC-1** Collaboration" as a social competence, "**A-4** Critical thinking…"as a personal trait as well as "**B-1** Project management" belong to this list. Competence in non-functional CPS characteristics "**TNF-2** Interoperability" concludes the top seven's list.

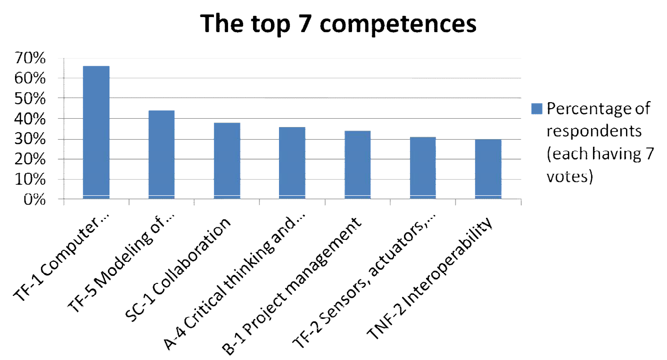

Fig. 2. The top seven required competences

To find out which competences were appreciated to what extent by all respondents and to investigate the variations caused by the diverse core responsibilities (teaching, research, engineering, and management) as well as by the differences in workplace (academia or industry) of the respondents, some descriptive data analysis was conducted. For this, 1) the number of votes given by respondents per competence was summed up; 2) the average, expected number of votes per competence was calculated (s. (1)); and 3) per competence a ratio of its votes to the expected value was calculated (s. (1)) (s. [22]).

$$expected = \frac{\sum_{i=0}^{n} v_i}{n}, \quad ratio_i = \frac{v_i}{expected} \tag{1}$$

$$v_i = number\ of\ votes\ for\ i-th\ competence\ or\ gap;$$
$$n = number\ of\ competences$$

Ratios were calculated for the whole group of the respondents, as well as for the representatives of each core responsibility and workplace. So for the whole group and per category, each competence got a positive ratio which means the frequency of their actual selections in comparison to the expected value. For instance, a value **x** which is greater than 1 means that the corresponding competence is selected **x** times more often than expected. In contrast a value **x** between 0 and 1 means that the corresponding competence is selected x times less often than expected. The results of this analysis are presented in Table III in the columns beneath the area "Question Q1: Selected Competences' Ratios". Those ratios that are greater than 1 have been marked with color.

It can be seen that four of six competences of category "CPS Foundations" are appreciated as very important. Competence "**TF-1** Computer science/ SW Engineering" was over 3 times more often selected than in average by all of the respondents. Two of seven non-functional CPS characteristics "**TNF-1** Security and privacy" and "**TNF-2** Interoperability" are considered nearly equally important by the different respondents' categories. Engineering competences "**TE-5** Systems of Systems" and "**TE-2** Industrial automation…"are seen by all of the respondents as important. Additional to the technical competences a business competence "**B-1** Project management" and two social competencies "**SC-1** Collaboration" and "**SC-2** Communication" are considered important for CPS engineers. Last but not least personal trait "**A-4** Critical thinking…" is extremely appreciated by all of the respondents.

However, some variations can be noticed in the views of the respondents within different categories. For instance, non-functional competence "**TNF-7** Human factors and usability", business competence "**B-1** Project management" and social competence "**SC-1** Collaboration" are highly appreciated by managers in contrast to the respondents within other categories. For engineers, the competence "**TE-1** Engineering process" is much more important than for other respondents. Competences "**TE-2** Industrial automation" as well as "**A-1** Analytical skills" and "**A-4** Critical thinking…" are especially important for both engineers and researchers. Teachers mostly believe that such technical competences as "**TF-2** Sensors, actuators, embedded systems" "**TF-3** Discrete and continuous mathematics", and "**TF-4** Application of sensing, actuation…" are especially needed for CPS engineers. "**A-6** Lifelong learning" is seen by teachers as an important personal trait. For respondents from industry such competences as "**TNF-2** Interoperability", "**SC-1** Collaboration" and "**A-5** Cross-disciplinary thinking" are after "**TF-1** Computer science/SW engineering" the second significant competences of CSP engineers.

*E. Results of question **Q2** – Competence Gaps*

Question Q2 was aimed to find out which gaps in the competences of CPS engineers are seen by the respondents as critical. Figure 3 shows the top five critical competence gaps of CPS engineers with the percentage of respondents who chose them. It can be seen that gaps in non-functional competence "**TNF-1** Security and privacy" (33% of the respondents) and in personal attribute "**A-5** Cross-disciplinary thinking" (28%) are considered critical by the respondents. They are followed by the gaps in "**TF-1** Computer science/ SW Engineering" (25%) as well as "**TF-5** Modeling of heterogeneous systems" and "**SC-2** Communication" (each 23%)

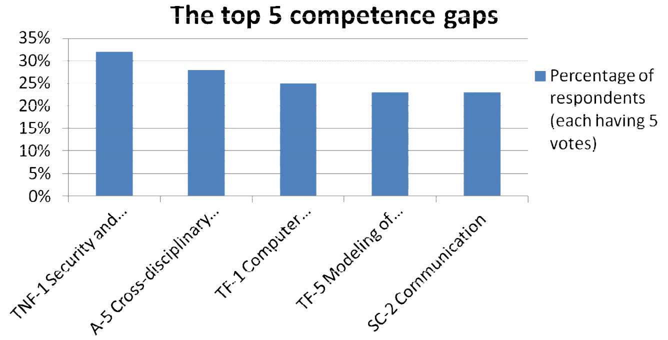

Fig. 3. The top five competence gaps

To find out how the respondents saw the individual competence gaps and to investigate the variations caused by diverse core responsibilities (teaching, research, engineering, or management) as well as by the differences in workplace (academia or industry) of the respondents, the same descriptive data analysis as for question Q1 was conducted. For this, 1) the number of votes given by the respondents per competence gap was summed up; 2) the average, expected number of votes per competence gap was calculated (s. (1)); and 3) per competence gap a ratio of its votes to the expected value was calculated (s. (1)) (s. [22]). This was done for the whole group of the respondents, as well as for the representatives of each core responsibility and workplace. The results of this analysis are presented in Table III in the columns beneath the area "Question Q2: Selected Competence Gaps' Ratios". Those ratios that are greater than 1 have been marked with color.

Taking a look at the technical competence gaps (categories "CSP Foundations", "Non-functional characteristics of CPS", and "Engineering") it can be seen that all categories of respondents unanimously saw that two competence gaps were large in each technical category: "**TF-1** Computer science/ SW Engineering" and "**TF-5** Modeling of heterogeneous systems", "**TNF-1** Security and privacy" and "**TNF-7** Human factors and usability", "**TE-3** System-level approach" and "**TE-4** Systems integration across domains". In contrast, the gap in non-technical and soft competences seen by the respondents was much larger than in the technical ones. Three-quarter of competences of in category "Social competences" and two-thirds of competences of category "Personal traits and attitudes" were seen as being large gaps.

However, some variations can be noticed in the views of the respondents within different categories. For instance, teachers see the largest gaps in the technical competences, mostly in CPS foundations and engineering. They also consider that there is a gap in the social competence "**SC-1** Collaboration" and such personal attitudes and "**A-4** Critical thinking". Managers see the largest gaps in the business and social competences as well as in the personal attitudes.

TABLE III. RATIOS OF COMPETENCES AND COMPETENCE GAPS TO EXPECTED VALUE

Cat	Competences	Question Q1: Selected Competences' Ratios							Question Q2: Selected Competence Gaps' Ratios						
		All responders	**Teaching**	**Research**	**Engineering**	**Management**	**Academia**	**Industry**	**All respondents**	**Teaching**	**Research**	**Engineering**	**Management**	**Academia**	**Industry**
CPS Foundations	Computer science/ SW Engineering **(TF-1)**	3.16	3.36	3.13	3.18	3.08	3.12	3.15	1.61	1.98	1.83	1.39	0.54	1.67	1.31
	Sensors, actuators, embedded systems **(TF-2)**	1.48	2.77	1.15	1.99	1.54	1.39	0.90	0.72	0.85	0.61	0.56	1.08	0.83	0.0
	Discrete and continuous mathematics **(TF-3)**	0.58	1.19	0.47	0.80	0.0	0.58	0.00	0.95	1.70	0.84	0.83	0.00	1.04	0.0
	Application of sensing, actuation, control, communication, and computing **(TF-4)**	1.11	1.98	0.99	1.19	1.16	1.15	0.45	0.95	0.57	0.84	0.83	0.00	0.97	1.31
	Modeling of heterogeneous and dynamic systems integrating control, computing, and communication **(TF-5)**	2.09	1.78	2.30	1.99	1.16	2.07	1.35	1.49	1.98	1.60	1.39	0.54	1.46	1.31
	CPS development life cycle **(TF-6)**	0.66	0.40	0.57	0.60	1.16	0.62	1.35	0.72	0.85	0.84	0.00	0.54	0.83	0.00
Non-functional characteristics of	Security and privacy **(TNF-1)**	1.36	1.58	1.25	1.19	0.77	1.44	0.90	2.09	1.98	2.14	1.67	1.63	2.23	1.31
	Interoperability **(TNF-2)**	1.44	0.99	1.46	1.59	1.16	1.30	2.25	0.89	0.85	0.92	1.67	1.08	0.70	1.96
	Reliability and dependability **(TNF-3)**	0.78	0.79	0.78	0.80	0.77	0.72	0.90	0.72	0.57	0.76	0.00	0.00	0.77	0.65
	Power and energy management **(TNF-4)**	0.49	1.19	0.31	0.80	1.16	0.53	0.00	0.36	0.85	0.23	0.28	0.00	0.35	0.00
	Safety **(TNF-5)**	0.45	0.20	0.47	0.40	0.00	0.48	0.45	0.36	0.57	0.31	0.00	0.54	0.35	0.00
	Stability and performance **(TNF-6)**	0.53	0.20	0.52	0.80	0.00	0.58	0.00	0.60	0.28	0.61	1.11	0.54	0.42	0.65
	Human factors and usability **(TNF-7)**	0.82	0.79	0.78	0.80	2.70	0.77	1.35	1.31	1.70	1.22	1.11	1.63	1.32	1.31
Engineering	Engineering Process **(TE-1)**	0.94	1.38	0.78	1.59	0.77	0.96	0.45	0.66	1.13	0.61	0.83	1.63	0.42	1.96
	Industrial automation, plant modeling **(TE-2)**	1.31	0.99	1.25	1.59	0.77	1.15	1.80	0.95	0.57	0.99	1.11	0.54	1.04	0.65
	System-level approach **(TE-3)**	0.66	0.59	0.78	0.40	0.00	0.62	0.45	1.13	1.13	1.22	0.83	1.08	1.04	1.96
	Systems integration across domains **(TE-4)**	1.27	0.40	1.41	0.80	0.77	1.25	0.90	1.01	1.98	1.15	0.83	2.17	0.97	1.96
	Systems of Systems **(TE-5)**	0.99	0.99	1.10	1.19	1.93	0.91	1.35	0.95	0.57	1.07	0.56	0.54	0.97	1.31
Business &	Project management **(B-1)**	1.64	0.99	1.51	1.19	2.31	1.59	1.80	1.31	0.85	1.30	1.67	1.08	1.39	0.65
	Economics **(B-2)**	0.37	0.59	0.21	0.40	0.77	0.38	0.45	0.95	0.85	0.92	0.83	2.17	1.04	0.65
	Humanities (e.g. anthropology, sociology) **(B-3)**	0.29	0.00	0.21	0.20	0.39	0.34	0.00	0.72	0.28	0.53	0.83	2.17	0.56	1.96
	Legislation **(B-4)**	0.29	0.00	0.26	0.20	0.77	0.29	0.45	0.24	0.00	0.23	0.00	0.54	0.28	0.00
Social	Collaboration **(SC-1)**	1.81	1.19	1.88	1.19	2.70	1.73	2.25	1.07	1.70	1.07	1.67	0.54	1.11	0.65
	Communication **(SC-2)**	1.31	0.59	1.36	1.39	1.16	1.39	0.90	1.49	0.57	1.45	1.11	2.71	1.39	2.61
	Technical writing **(SC-3)**	0.66	0.79	0.68	0.00	0.39	0.62	0.90	0.72	0.57	0.69	0.83	0.00	0.70	0.00
	Presentation **(SC-4)**	0.45	0.79	0.42	0.00	0.00	0.48	0.45	1.25	0.85	1.22	1.39	1.63	1.25	0.65
Personal traits and attitudes	Analytical skills **(A-1)**	1.19	0.79	1.31	1.19	0.39	1.11	1.35	0.60	0.57	0.46	1.67	0.54	0.70	0.00
	Creativity **(A-2)**	0.99	1.19	0.94	1.19	0.77	1.01	0.45	1.07	1.13	1.15	0.56	0.00	1.18	0.65
	Entrepreneurship, successful transferring plans into reality **(A-3)**	0.33	0.20	0.37	0.00	0.39	0.34	0.45	1.31	1.42	1.37	1.39	2.17	1.32	1.96
	Critical thinking and critical attitude towards technological developments **(A-4)**	1.73	1.38	1.72	1.99	1.16	1.63	1.35	1.25	1.70	1.30	2.50	0.54	1.25	0.65
	Cross-disciplinary thinking **(A-5)**	0.99	0.79	0.99	0.60	1.16	0.82	2.70	1.85	1.13	1.76	2.23	2.17	1.60	3.92
	Lifelong learning **(A-6)**	0.66	1.19	0.63	0.80	0.77	0.62	0.45	0.72	0.28	0.76	0.28	1.63	0.83	0.0

So, they rated the gaps in "**B-2** Economics", "**B-3** Humanities", "**SC-2** Communication", "**A-3** Entrepreneurship…" and "**A-5** Cross-disciplinary thinking" over two times larger as in average. Engineers see the biggest gaps in social competences and personal traits as well. The representatives of industry see the biggest gaps in competences "**A-5** Cross-disciplinary thinking" and "**SC-2** Communication" as well as in the nearly all engineering competences.

IV. Conclusions and Outlooks

The survey and its results presented in this paper identify the requisite competences of CPS engineers and the competence gaps currently existing in CPS engineers.

The requirements for competences and existing competence gaps were investigated from two perspectives:

- working place - academia and industry, and
- responsibility areas – teaching /research /engineering /management.

All respondents, independent of their responsibility areas and working places, appreciate the majority of the CPS foundational competences as important. Non-technical competences like project management, collaboration and communication as well as such personal traits as critical thinking and analytical skills are also highly appreciated by all categories of the respondents. It is interesting to notice that the representatives of industry and management especially emphasize project management and collaboration as well cross-disciplinary and critical thinking. In contrast, the representatives of academia and teaching put more attention in CPS foundational competences.

The majority of competence gaps are seen by the respondents in CPS security and privacy topics, project management as well as in nearly all social competences and personal traits. Cross-disciplinary thinking, entrepreneurship, critical thinking and creativity are personal attributes which are missing in today's CSP engineers. Interestingly, the representatives of industry and management see the larger gaps in engineering, business and social competences as well as in personal traits than in CPS foundational competences. Contrary to this, the representatives of academia and teaching see larger gaps in CPS foundational and CPS non-functional competences.

The results of this research will be utilized in further development of a novel task-centric holistic agile approach on teaching CPS (T-CHAT) [23] and in development of new CPS courses that are based on this approach.

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