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The role of competence networks in the era of Cyber-Physical Systems - promoting knowledge sharing and knowledge exchange

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Abstract. Needs for new engineering methodologies, curriculum renewal, and new forms of education and training arise, as Cyber-Physical Systems are becoming smarter, more automated, connected and collaborative. In this setting, the use of competence networks, i.e. non-profit collaborations between industry and academia aiming to promote learning and knowledge creation, stands out as a promising approach. Drawing upon experiences from the Innovative Center for Embedded Systems, a KTH-Industry cross-disciplinary and multi-domain competence network for students, practicing engineers, managers, and academic faculty, we describe and reflect on challenges and lessons learnt during the 11 years of operation of the ICES network. The findings support a need to emphasize knowledge sharing and exchange encompassing multiple disciplines and cross-domain industrial experience. A competence network acts as a social network that facilitates communication, learning and knowledge creation for both individuals and organizations. Competence networks can thus act as tools for policy makers, creating incentives for life-long learning inside companies. A focused engagement and activities directed towards stakeholders help to establish trust, providing potential for agile and persevering forms of cooperation.

Keywords. Cyber-physical systems, Embedded systems, Competence networks, Learning networks, Industry-academia collaboration, Engineering education, Life-long learning, Continued Education

1. Introduction

Cyber-Physical Systems (CPS) are evolving to take on new challenging tasks in more open and collaborative environments, fueled by continued technological advances and strongly driven by commercial opportunities. This evolution is seen on different levels, for example, from smart machines, over collaborating machines and humans, to smart transportation systems. The evolution takes place in virtually all - and new - domains, including but not limited to manufacturing, medtech, energy and transportation. To manage such new sophisticated tasks, CPS are in turn evolving to become more intelligent, autonomous and connected. The connectivity in itself enables learning, CPS upgrading, lifecycle management and collaboration, facilitating service- or function-based business models. As a result, CPS will be playing an increasingly important role in societal infrastructure. However, this evolution clearly also corresponds to an increasing CPS complexity, reflecting the inherent complexity of the new capabilities and the environments, including a larger degree of uncertainty and change over time, [1].

One implication of the growing complexity is the need for new CPS engineering methodologies, [1, 3]. The corresponding requirements on engineering capabilities put increasingly stringent demands on the continuous gathering, analysis and use of knowledge by those developing CPS. Industrial needs regarding CPS education are thus changing, with *competence provisioning including life-long learning for organizations* becoming crucial. The move

towards rapidly evolving multi-technology systems moreover call for renewed university curricula as well as their more frequent updating. We believe that there is a need to revisit and think beyond traditional engineering education in dealing with these challenges. The rising importance of life-long learning underscores the need to complement traditional education programs with new forms of training, targeting professionals at different stages of their careers. In this setting, the use of competence networks, i.e. non-profit collaborations between industry and academia aiming to promote learning and knowledge creation, stands out as a promising approach to deal with the outlined issues. In this paper we focus specifically on the learning aspects in terms of knowledge sharing (in terms of dissemination) and knowledge exchange (in terms of active bidirectional interactions).

The aim of this paper is to discuss challenges and lessons learnt associated with competence networks in the context of CPS with the purpose to better address competence provisioning for becoming and existing professionals. We draw upon our experiences from ICES, the Innovative Center for Embedded Systems, a KTH-Industry cross-disciplinary and multi-domain competence network. ICES focuses on activities to support students, practicing engineers, managers, and academic faculty, and has in 2019 been operational for 11 years.

The paper disposition is as follows. We introduce the ICES network in Section 2 and in Section 3 summarize challenges related to competence provisioning (as noticed by state of

the art and experienced in the ICES network). In Section 4, we describe lessons learnt during the operation of the ICES network, and finally in Section 5, we reflect on the gained experiences and discuss generalizability.

2. The ICES Competence Network

The ICES center at KTH in Stockholm was inaugurated in September 2008, with six initial industrial partners with the specific goals to bridge fragmented disciplines at KTH in embedded and cyber-physical systems, and to strengthen collaboration with industry. During its 11 years of operation, ICES has grown, and now has more than 30 companies as partners. ICES is funded by the partners, innovation projects, and KTH. The turnover is in the order of 200 kEUR, complemented by in-kind efforts of the same order of magnitude.

When ICES was created, the needs and concerns of the funding organization were elicited. This resulted in the realization that while faculty targeted research, the industrial partners saw competence provisioning as an even more fundamental issue at hand. Industry wanted to recruit students and get access to KTH faculty. As a result, the center was formed as a “competence network”, with the purpose to create a platform for facilitating contacts among faculty, students and industry. *Over the years, the importance of knowledge sharing and knowledge exchange have grown with the ever increasing complexity of CPS, [2, 3].*

Within ICES a view of shared concerns in the area was developed early on, renewed and evolved over the years with the increase of complexity and a naturally growing scope, but without any other major changes, [3]. The guiding vision of ICES is as follows: *achieving a prospering ecosystem for industry and academia, catalyzing world-class education, research and innovation.* The strategic objectives include, (i) a focus on key identified and shared concerns, (ii) acting as a *network, catalyst and competence provider* directed towards the key stakeholders of the center, and (iii) creating *synergies* with related initiatives.

The *networking role* of ICES, concerns connecting and establishing collaboration among the stakeholders (e.g. connecting industry with students and academic faculty), but also to stimulate interactions within these groups of stakeholders (e.g. connecting relevant academic disciplines). The *catalyst role* of ICES involves creating activities that are beneficial for its stakeholders, such as initiating collaborative research projects and new educational programs at the university. The role as *competence provider* includes cross-domain knowledge sharing, access to competence through the network, improving and renewing education including life-long learning, and stimulating the interests in engineering by young people. The role to create *synergies* includes collaboration with related initiatives, including related KTH research centers., .

ICES workgroups form a central part the activities. Workgroups act as operational groups to achieve strategic

objectives. There is for example a workgroup focused on creating opportunities for continued education. This group has investigated thematic topics prioritized by industry and initiated corresponding courses on topics such as functional and system safety, systems thinking, interoperability and testing. In addition, various models for implementing courses suitable for industry have been investigated. Course formats have included half-day introductory courses and intensive courses for industry, often with PhD and Master student participation. The courses have been designed to either address needs for providing topical overviews (relevant for many engineers and academics), or to provide in-depth knowledge (typically for experts).

The intensive courses have often been arranged as 2+2 intensive days with at least a couple of weeks in-between the sessions for reflection and project work. The number of participants have been in the range of 20 people. The overview courses have typically engaged lecturers representing different disciplines at KTH as well industrial experience lectures. The courses have benefitted from having multiple industrial domains present as participants, providing a further sharing of experiences. While the courses have received positive evaluation and been seen as successful, we have over the years experienced that participants have become increasingly busy, leading us to elaborate new ways for arranging continued education (see further Section 3).

Another workgroup – the “Learning network”, manages a number of “Competence groups” in which industrial experts and KTH faculty meet, organize activities (such as workshops), and exchange experiences on topics of common interest. The topics addressed by the competence groups include for instance artificial intelligence, safety, system engineering, and R&D management. The competence groups have evolved different profiles in terms of the types of activities they have chosen to organize. For example, the safety group has emphasized the organization of a relatively new Scandinavian conference that provides a venue for cross-domain industrial interactions and for meeting academia. The systems engineering group has instead focused on introducing systems thinking and systems engineering into KTH education. The competence groups receive administrative support from the ICES office and a small budget, and report to the ICES board.

3. Challenges and the State-of-the-Art

Organizing competence provisioning and life-long learning – as crucial for managing future CPS – faces a number of challenges. This section describes four challenges, identified by the State-of-the-Art and experienced in the operation of ICES. The challenges encompass both engineering education renewal as well as the use of competence networks.

Education is not prioritized. At Higher Education Institutions (HEI), education normally has a much lower status than research; this is also true for continued education [4.

7]. Firstly, a direct implication of this is the relatively small adoption of best practices in engineering education, [5]. While renewal usually takes place on the course level, such changes are usually incremental and do not address major changes required for curriculum renewal. Secondly, as faculty tend to prioritize research, activities in competence networks might come to depend on the few educational enthusiasts that do exist. This has made it difficult to provide continuity for some of the activities in ICES. Thirdly, there is thus a lack of funding for competence networks. As a competence network, ICES has provided more indirect (and harder to value) outcomes compared to research projects – making it more difficult to argue for the importance of the activity. Fourthly, different aspects of competence networks are addressed by different initiatives and organizations, leading to a fragmentation of efforts, a lack of coordination, and a limited sharing of educational best practice. Especially the rate at which best practices in education are adopted is hurt by this lack of priority. Interestingly, this happens at a time when engineering programs are tasked with fostering new skills, such as cultural awareness, sustainability, innovativeness and entrepreneurship. Driven by demands from firms and the opening up of new career paths, this demand for new content conflicts with the fact that engineering curricula are already stretched to their limits. However, both new teaching practices and learning environments have been suggested as solutions to this dilemma [9]. Competence networks might thus be a solution to this dilemma by providing a new, industry-close learning environment based on up-to-date educational practice.

The paradox of strong needs, but a (perceived) lack of time. Industrial companies agree that competence networks are increasingly important. Network cooperation can be seen as beneficial by generating complementarities and inter-firm learning, [10]. It is typically also an efficient way to share knowledge as the associated breadth of competencies can be exploited over a long time. Networks that contain both industry and academia are often of special interest to firms, as they can use these networks to access new technology and specialized consultancy. However, academic institutions can also benefit from such networks when covering the whole state of the art of a topic area is beyond any single institute – they allow academics to identify important topics, and to understand exploitation better. However, most industrial stakeholders also perceive themselves as very busy. This can create an imbalance in addressing short-term vs. long-term needs, making it difficult to engage people in competence network activities in a continuous manner. The observed difficulty in prioritizing even intensive courses and the need to provide more efficient course development, has led ICES to emphasize digitalization of modularized courses as an ongoing initiative. We believe that a supporting social context further strengthens such efforts (see section 5.3).

Communication overflow and access to relevant competence. Identifying suitable communication channels and getting the attention of stakeholders is increasingly challenging. Organizations do not have an easy time engaging with organizations that are not similar to themselves due to difficulties to identify and absorb knowledge that is different from their own [8]. This is by necessity the case for academic institutions and firms. Moreover, it is non-trivial in many cases to find relevant information and expertise in academia, largely because of the accentuated growth and fragmentation of knowledge. In addition, while individuals may retain contacts from their engineering education, their careers may more rapidly than before lead them into new areas of knowledge, requiring the renewal of contacts with academia.

Breadth vs. depth and multidisciplinary required in dealing with complexity. As described in Section 1, the number of theories, technologies and skills required to master future CPS are growing at a steady pace. For example, the expanding cyber-side requires that engineers and managers (regardless of discipline) have at least a basic understanding of data analytics, artificial intelligence, and cybersecurity, and the complexity increase strongly motivates systems and design thinking for all CPS engineers. As a further example of the renewal required, computer scientists and software engineers, need to understand physical implications including safety risks, in working with the cyber-side of CPS. Similarly, traditional physical-, embedded- and mechatronics-related disciplines need a better understanding of cyber-security risks. The challenges here are that curricula cannot just continue to grow, requiring trade-offs and new educational approaches. Moreover, incorporating the required changes requires skills that would typically require multidisciplinary (cross-department / -school) collaboration, representing a challenging endeavor in a university because of its typical fragmentation into disciplinary structures, [4, 5]. The low status of education further exacerbates these challenges.

4. Lessons learnt

Based on the experiences from ICES we have identified a number of practices that stand out as important for the long-term evolution and fruitful operation of the network.

Shared visions and goals. ICES early on put significant effort into identifying key stakeholders and their needs. For example, it is clear that there is a large demand for CPS engineers. This creates strong incentives for industry to engage with HEI, providing benefits by helping shape new educational programs. Accordingly, we have also continuously had a dialogue with stakeholders to improve and introduce educational practices. However, the primary result of these shared visions and goals has been the ability to maintain a stable and well-defined scope for ICES. Rather than expanding into all types of activities, ICES has worked to establish collaborations with related organizations and

networks. As concrete examples, ICES has collaborated with INCOSE Sweden, with multiple jointly organized workshops, and one of the first initiatives in ICES was to pave the way for a KTH membership in the ARTEMIS Industry Association, which gathers actors in Embedded & Cyber-Physical Systems within Europe.

A diverse board and a decentralized, networked organization. The ICES board has generally been rather large, to engage the organizations and to spread information. Furthermore, based on competence- and working groups, the organization is decentralized. The board of ICES has always had a strong presence of industrial representatives, including the chairperson. The industrial engagement has helped to provide motivation to KTH management when proposing educational renewal and in ensuring long-term financial support from industry.

Student engagement. Student representatives on the board and in work groups provide valuable insights into education at KTH, communicate ICES activities to other students, and facilitate student interactions with industry as well as with academic faculty. The ICES board currently has representatives from three engineering programs, as prioritized among the large set of KTH programs. Examples of student impact include having them to contribute feedback for course improvements and for providing new ideas of interactions with industry. These ideas have for instance resulted in the concept of “Pizza with an engineer” - events hosted by industrial partners where students can talk directly to young engineers in an informal setting and dedicated MSc thesis fairs. These types of events have been highly appreciated by both students and company representatives.

A code of conduct instead of agreements. ICES is not based on complex, legal agreements, but rather relies on a basic code of conduct. Despite many of the partners being competitors, the benefit of long-term competence development is seen as important enough to merit cooperation. Having a competence network hosted at a HEI also enhances the trust of the participating organizations, as the HEI is seen as neutral ground in comparison to other stakeholders. Generally, information that partners bring to the network is thus considered to be open. When initiatives that require agreements come into play, such as when ICES catalyzes a research project, these are kept separate from ICES activities.

A practice and experience based perspective on educational development. It is difficult to integrate academic disciplines. Higher education institutions have strong traditions and are slow to change. Moreover, faculty are rewarded for specializing, and there is a lack of incentives to integrate across disciplines. Similarly, academic teachers often lack first-hand experience with industrial applications, creating a gap between the theory taught and the industrial concerns regarding CPS. A further inherent difficulty concerns limited teaching insights regarding issues related to

the lifecycle of systems; these represent example areas where industry can contribute valuable experiences.

For engineering students, the ICES competence network has worked to address these concerns, by facilitating arrangements of student study visits to industry, industrial guest lecturers, and for identifying and running industry sponsored capstone projects. The industrial network further strived to make industrial needs for engineering education explicit and thus contributed to convincing university leadership of the importance of introducing a new international master-level program in Embedded Systems at KTH in 2011. Given that KTH already had many programs, the industrial support for launching a new program was decisive in motivating its launch. The program was designed as a collaboration between four schools (computer science, ICT, electrical engineering, and industrial engineering and management), each providing their “best courses” to the program – thus making the program more multidisciplinary. The interest in the program has grown from its start. 2019 the program had about 700 applicants worldwide, with 335 having the program as its first priority. The program scores well in course evaluations and is highly appreciated by the industrial partners in ICES.

The network has led to initiatives where company partners offered to provide course modules to engineering students. In practice, these modules have often been implemented as part of capstone courses. One example of this is the integration of a systems engineering module, provided by experienced industrial systems engineers, including insights into challenges of real project development and lifecycle concerns. The actual course was performed over three days in a six working day period, composed of lectures and an integrated mini-project, focusing on a mission for an ‘Emergency evacuation rover’ (students were provided with a Lego mindstorms kit and a basic pre-built robot). The number of students were about 65, [5, 6]. Another example refers to a practical and engineering experience related module on EMC, provided by an ICES company partner to engineering students.

All these efforts highlight that faculty and industry, together, possess a broader set of knowledge and skills – which if utilized properly, can significantly improve engineering education. Perhaps most critically, it points at how industry can offer an outside-in perspective, helping academia identify and carry out educational activities outside the traditional academic scope, facilitating multidisciplinary and fruitful combination of theory and practice.

Best practice exchange across industrial domains. During the early years of ICES, we discovered that industrial partners had surprisingly common views on challenges across diverse domains and that they enjoyed meeting to exchange best practices across domains. This finding has since then influenced most of the activities within ICES, including the competence groups and the organization of many events. For example, the Scandinavian Conference on

Systems and Software Safety, which ICES has been arranging since 2015 in Stockholm, has engineers from multiple industrial domains attending (e.g. railway, automotive, medtech, avionics, etc.). Many of the attendees share similar concerns (such as how to deal with safety and cybersecurity, safety for AI-based systems, etc.) and enjoy the exchange of best practices. Another example of this is the R&D managers' competence group that meets regularly to exchange knowledge on shared problems and practices of interest.

Competence groups. In operating the ICES competence groups (as introduced in Section 2), a number of important success factors have been identified. Fundamental requirements for creating well-functioning competence groups include the aggregation of a critical mass, in combination with highly motivated individuals who are able to engage other interested stakeholders in a sustained way. Accomplishing this requires qualified insights into the specific area at hand, communication skills, and an ability to identify interesting and relevant topics for meetings and other activities. Since experts are very busy and not always inclined towards prioritizing networking, competence groups need dedicated support for their operation (essentially a person who helps in setting up meetings). Furthermore, it is important to monitor the competence groups to understand how they should best be developed and what support is needed in doing so. Another critical activity is to continuously review and, when needed, renew the overall portfolio of competence groups, by starting new ones and closing down the ones that no longer display sufficient activity, or have become less relevant for the stakeholders.

5. Discussion

In this section, we reflect on the role of competence networks given the described Challenges (Section 3) and Lessons learnt (Section 4). We finally discuss generalizability of our findings.

5.1 Competence networks - an effective mechanism for competence development

Companies are frequently reluctant to invest in competence development and often appear to prefer having a higher employee turnover to "shift competences". This is most likely costly, but it is easier to argue for hiring new employees with desired competence than arguing for a budget to support life-long learning. One reason for this may be that central human resources absorbs much of the costs for hiring and laying off employees, whereas continuous competence development costs are typically carried by the business units. Given the rapid speed of technological evolution, it is hard to see a way forward, which does not emphasize life-long learning. Our lessons learnt indicate that cost-efficient competence networks can form part of strategies for updating competences, as compared to the true costs of hiring new people. Through its competence groups and

cross-domain activities, ICES acts as a broker of knowledge, passing knowledge across organizational and domain boundaries. This is enabled by playing down the need for agreements, aligning participants towards viewing ICES as a neutral ground where knowledge can pass between public and private organizations.

Competence networks can thus be tools for policy makers towards creating incentives for life-long learning inside companies, rather than only supporting educational activities for those who have lost their jobs due to outdated competence profiles.

5.2 Continuous engagement supporting effective knowledge exchange

As industry and academia are not similar to each other, they face difficulties when communicating. Competence networks even constitute unusual entities in the world of academia, especially in comparison to traditional research centers. Research centers usually involve companies offering center- or project funding, and in return they are invited to a few workshops per year and a committee for deciding on research projects. ICES on the other hand offers opportunities for continuous interaction in terms of work groups, competence groups, board involvement, workshops and conferences. To access the network thus requires additional efforts in understanding what the network and groups are about, and then further time and prioritization in order to keep a high level of engagement. On the other hand, the result of the continued interaction is a better matching of industrial needs and academic knowledge, as well as a reduction of the efforts needed to diffuse and use knowledge. This is arguably facilitated by maintaining focus on a well-defined scope. The focused engagement and activities that explicitly supports the stakeholders help to establish trust, structure and promote long-term collaboration.

Participants in ICES activities know why they engage in them, and knowledge passes between individual participants directly rather than first having to be summarized centrally. This makes ICES more agile than traditional forms of cooperation, and with its 11 years in existence also more persevering, e.g. as compared to research centers.

5.3 A social network in support of the individual engineer

As industry works with increasingly complex systems and since academia cannot just continue to add to curricula, academia and industry must cooperate to make education more relevant. Industry can for example contribute experience related to complex multidisciplinary engineering and their full lifecycles, complementing traditional faculty competence and academic courses. Academia has strongholds with deep knowledge in the existing disciplines. Competence networks allow academia to both learn from industry, and to teach what they know in an effective way by tapping into an outside-in perspective on educational development.

Furthermore, the use of competence networks has this far received much less attention than for instance the use of online courses, which are often held forward as a cost-efficient alternative for competence provisioning. However, formal engagement in a social network makes it easier and more legitimate to prioritize learning activities, as compared to when this is regarded as an individual activity. This legitimacy would likely be enhanced by strong student engagement and the continuous sharing of best practices, as the engagement of a firm's engineers has positive secondary effects for recruitment and staying competitive. Competence networks such as ICES can thus not only gear continued education towards a format that fits industry, they can also make it easier for the individual engineer to engage in continued education.

5.4 Generalizability of the lessons learnt

The operations of the ICES competence network have evolved in the larger Stockholm area (Sweden). Many of the lessons learnt should be valid also in other settings. However, differences in regional characteristics need consideration in any attempt to draw upon the findings from ICES. The Swedish setting is characterized by free university education, and a tradition of governmental sponsorship of research and education. Correspondingly, there is limited direct industrial sponsoring of such activities. The culture and regional scale have most likely been important in creating an environment of trust without formal agreements, where people participate and share information quite openly. Establishing trust among stakeholders will be important in setting up similar competence networks.

The trends and challenges with CPS are not specific to any region. The industrial presence and the types of domains related to a region could however vary. A broader spectrum of CPS application domains – such as we are fortunate to experience with ICES, certainly implies that it should be easier to set up a competence network. Engaging in a network to share experiences, may be easier across domains since there is less competition.

Further work should address dissemination of best practices on competence networks. Proactive measures should be considered regionally to implement such networks in areas involving complex systems.

6. Conclusions

The emergence of smarter, more automated, connected and collaborative CPS, emphasizes needs for new engineering methodologies, curriculum renewal, and new forms of education and training. We have described challenges for competence provisioning and lessons learnt during the 11 years of operation of the ICES network. The lessons learnt include generic practices related to stakeholder engagement and alignment, bi-directional exchange between academia and industry, and best practice exchange across industrial domains.

A competence network acts as a social network that facilitates communication, brokerage, learning and knowledge creation for both individuals and organizations. The findings support a need to emphasize knowledge exchange encompassing multiple disciplines and cross-domain industrial experiences/best practices. For the world of complex CPS, interactions with industry helps HEI's to understand connections and gaps between disciplines. Competence networks support continuous competence development for both becoming and existing professionals, and can thus serve as tools for policy makers in creating incentives for life-long learning inside companies, rather than only supporting educational activities for those who have lost their jobs. The focused engagement and activities explicitly supporting the stakeholders help to establish trust and promote long-term collaboration. This provides the potential for agile and persevering forms of cooperation.

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