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What to Consider at the Development of Educational Programs and Courses About Next-Generation Cyber-Physical Systems?

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We live in an age in which new things are emerging faster than their deep understanding. This statement, in particular, applies to doing research and educating university students concerning next-generation cyber-physical systems (NG-CPSs). The fast evolution of this system paradigm would have expected a rapid and comprehensive paradigmatic change in research and education concerning this family of systems. However, this has not happened yet. Seeking a sufficient explanation, this paper reviews the current literature and attempts to cast light on the most significant recent developments in the field of NG-CPSs. The main assumptions of the authors are that research and education should appear in harmony in academic knowledge acquisition and distribution processes and that the academic education of NG-CPSs should be organized and conducted according to a defendable future vision. Combining the results of a broadly based study of the literature with prognostic critical thinking and personal experiences, this review-based position paper first discusses the current socio-techno-scientific environment, the involved stakeholders, and the demands and two approaches of truly systems-oriented education. Then, it concentrates on (i) the recognized limitations of mono- and interdisciplinary research, (ii) supradisciplinary organization of research, and (iii) transdisciplinary knowledge generation for NG-CPSs. As main contributions, the paper (i) identifies and analyzes the latest theoretical, engineering, and technological developments, (ii) reveals the major trends and their presumably significant implications, and (iii) presents several thought-provoking findings and makes propositions about the desirable actions.
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1 Introduction

We live in an age in which new things are emerging faster than their deep understanding. This statement, in particular, applies to doing research and educating university students concerning next-generation cyber-physical systems (NG-CPSs). The major development trend is moving from mode 1 science toward mode 2 science, which

- is more interested in finding solutions for large-scale industrially and socially created research problematics than making focused and limited scope empirical inquiries into well-formed existing research phenomena,
- assumes innovation-orientated thinking based on merging systems thinking, design thinking, and computational thinking, as well as on operationalization of transdisciplinary knowledge and deployment of pluridisciplinary inquiry methodologies toward this end,
- accepts rational analysis and knowledge synthesis as a full-value equivalent and complement of purely empirical studies completed by individual investigators using purely quantitative, purely qualitative, or even mixed methods, and
- gives the floor to expert opinions as well as to social stakeholders' intellect concerning policies, research, education, etc., even if it may raise the hazard of destroying the traditional culture and value system.

This paper intends to contribute to NG-CPSs education. In concert with many scholars, we posit that present-day research, education, implementation, and deployment of systems are influenced by an unfathomable multitude of developments and that this influence will be even stronger and more indecipherable in the foreseeable future. The education in this field is supposed to manifest as a complex problematics that cannot be separated from the scientific, technological, economic, social, and cultural environments and developments [1]. Our vision of the major influential trends and factors are shown in Fig. 1. As the arrows indicate, the concurrent scientific and technology developments (i.e., disciplinary convergence, supradisciplinary inquiries, and fusion of technologies), combined, on the one hand, with the study and transfer of synthetic systems knowledge as a novel productive asset, and, on the other hand, with transdisciplinary problem-solving and integral computational mega-/meta-modeling, are going to lead to a situation which is dominated by highly intellectualized, socialized, and personalized systems which will form clusters of self-organizing systems of systems and serve as responsible autonomous systems. In itself, each of these is as complicated as the whole they jointly form. The operational mechanisms of these trends and factors reflect causality, whereas their interaction leads to synergy, even if their roots are different. These will embody the notion of NG-CPSs [2]. In the remaining part of the paper, we project this vision to the research and education toward NG-CPSs with the intent to (i) cast light on the current situation, (ii) make an inventory of the most progressive approaches, and (iii) derive conclusions in the above-mentioned contexts. None of these efforts can be

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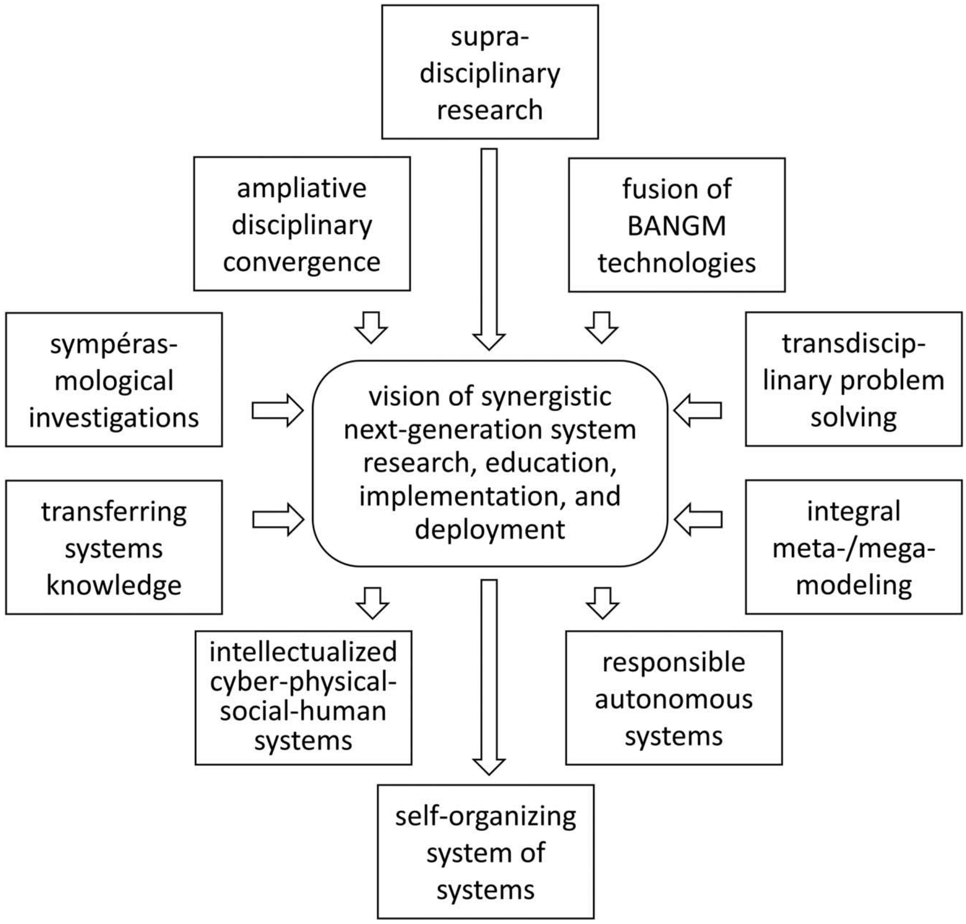

Fig. 1 Vision on synergistic next-generation system research, education, implementation, and deployment

exhaustive due to the apparent multi-faceted and complicated nature of the problematics.

Various increasingly complex global challenges are running parallel to the recent scientific, technological, and societal developments [3]. The integration of new technologies has social consequences that concern many different fields such as law, medicine, sociology, and psychology, and that are reflected in science and technology too. For example, (i) extreme energy and natural resource consumption due to over-industrialization, (ii) global population and economic changes threatening a sustainable future, (iii) social challenges, such as personal isolation and informational overload, as a result of the increasing digital communication and virtual interaction, (iv) ethical issues in the context of the application of artificial intelligence (AI) and biotechnology, and (v) cyber threats and malicious manipulations due to the extensive use of networks. It is becoming better comprehended that while technological progression offers benefits and technology can correct itself, rapidly developed and employed new technologies may cause previously not experienced problems and lead to the emergence of new challenges for humanity [4]. The economic clusters (societies, countries, companies, or individuals/groups) that can adapt to these technologies can achieve transformation by seizing new opportunities and managing economic and social inequalities. In almost every productive or servicing sector, the existing workforce is likely to change significantly, both qualitatively and quantitatively, due to the use of AI and automation technologies [5]. On the one hand, the intense globalization makes it difficult to preserve cultural diversity, and the prevailing dependence structures bear the potential to lead to cultural conflicts [6].

As a consequence of the ongoing convergence of scientific disciplines and integration of cutting-edge technologies, innovative system paradigms (e.g., deeply embedded systems, Internet of Things (IoT), AI-based systems, etc.) have emerged that cannot be realized within the boundaries of one single discipline, and without integrating the strengths of more than one technology [7]. The initial archetype of CPSs, in which the control and computational capabilities are integrated with physical components, is a typical manifestation of such systems [8]. Based on a purposeful integration of technologies, such as IoT, big data analytics, and machine learning, these systems can be tailored to find solutions for social problems [9]. The coexistence of convergence and divergence has led to the emergence of the concept of cyber-physical-social systems (CPSSs) [10]. The importance of CPSS is in the potential to provide solutions to complex societal problems that are difficult to address with traditional approaches [11]. Such disciplinarily augmented CPSs have been successfully deployed in fields such as healthcare, transportation, energy conservation, disaster management, and environmental monitoring [12], and are expected to gain even higher momentum in the coming years. They have also begun to embed human actors synergistically and to increasingly influence and transform almost every aspect of our lives.

Concerning the paradigm of CPSs, there is a chasm between the visions and views of the majority of the early pragmatic road setters and the current post-disciplinary visionaries. As touched upon above, many rapidly changing trends are influencing the manifestations of the paradigm of CPSs [13]. One of them is disciplinary complexification, which, on the one hand, increases their functional, architectural, implementation, and application complexity and heterogeneity, and, on the other hand, raises the need for integrative, cross-disciplinary (mechanical, electronic, computing, information, human, social, and management sciences) studies that however hardly meet the traditional research approach of mode 1 science [14]. This traditional framework of inquiry poses limitations, which are growing as the diversification of science concepts is growing and the value of disintegrated knowledge is decreasing [15]. In addition to empirical and theoretical research, computational modeling/simulation and massive data-based research methods have also become indispensable. In addition, both the object and the subject of investigations are changing as the focus of mode 2 science is shifting from naturally existing phenomena to complex industrially, socially, or politically created (scientific) problematics, and the knowledge generation needs intense collaboration in trans-disciplinary research communities [16].

At the current stage of scientific and technological progression, the effectiveness of the traditional education systems regarding integral dissemination and systems-orientated blending of knowledge is increasingly questioned [17]. Educational approaches preferring instructing and memorization, limit the critical thinking, creativity, and problem-solving skills of the students as well as their ability to apply knowledge in real-world situations is heavily debated. Nevertheless, it may prove to be overwhelmingly challenging for the so-called high-inertia approaches of organized learning to adapt themselves to the increased dynamics demanded by the rapidly changing technological and societal contexts and employment markets [18]. They have been criticized for not supporting lifelong learning adequately, which is also becoming increasingly important. Overcoming these challenges requires a holistic approach that includes educators, policymakers, technology developers, and the broader community [19]. Adopting innovative teaching methods, using technology responsibly, and promoting inclusive and equitable educational environments are key steps to overcoming these barriers [20].

The remaining sections of this paper are organized as follows: Sec. 2 discusses why and how we need to see the paradigm shift of NG-CPS. In Sec. 3, level-by-level knowledge associated with the potential stakeholders of the NG-CPS is presented. Section 4 forms a basis for the essence of a system-orientated education and competence profile, while Sec. 5 discusses the issues of coping with the associated topic and time holistic processes. Section 6 elaborates on the limitations of mono- and interdisciplinary research in NG-CPS, while an old-and-new research approach is suggested in Sec. 7. Some essential new ingredients of post-disciplinary education are presented in Sec. 8. Finally, Sec. 9 provides a closure with conclusions and suggested actions.

2 Next-Generation Cyber-Physical Systems

"The bull in a china shop." Perhaps, this idiomatic phrase provides the most succinct portrayal of the unsettled situation which is caused by the evidenced shift of the paradigm of CPSs [21]. The fact of the matter is that these systems have originally been conceptualized as an amalgamation of the physical world and the cyber world but they cannot be treated anymore as such. The recently studied and implemented systems deliver extended functionalities with which they cover some parts of the human and social worlds too (Fig. 2). This multidimensional shift of the original paradigm changes our view on the objectives, technologies, research, education, business, and even human mental models of engineered systems [22]. As a specific member of the family of hybrid systems, CPSs have also shown an unexpectedly large and still dynamically growing influence. This is deemed one manifestation of the systemic metamorphosis exposed by Garcia Martínez [23]. A kind of new humanism is also emerging in the techno-computerized society of the 21st century, which connects, among others, the borderless blending of sciences and disciplines, systems-established realities, AI-based cognitive problem-solving, and revitalization of historical/cultural myths as deterministic and distinguishing features, as discussed by Presutti [24]. The fast

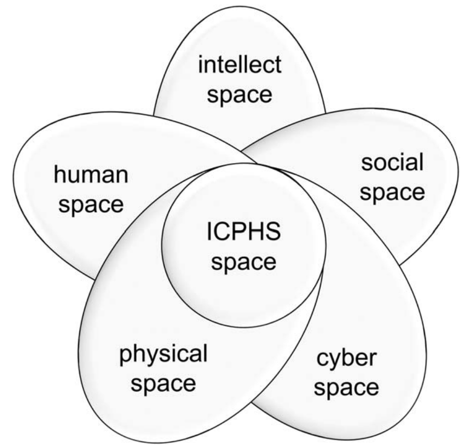

Fig. 2 Content spaces underpinning next-generation CPSs

evolution of this system paradigm would have expected a rapid and comprehensive paradigmatic change in research and education concerning this family of systems. However, this has not happened yet.

The root causes of the paradigm shift are the concurrently interplaying disciplinary convergence, technological integration, and wide-ranging practical application opportunities. These resulted not only in the complexification, intellectualization, socialization, and personalization of these systems but also in a non-definitive paradigmatic model and disciplinary ambiguities associated with the evolutionary trajectories and their interactions [25]. In addition to these, the application spectrum of CPSs has also widened despite many design challenges, the short-term utilization strategies, and unforeseen business implications. The current spectrum ranges from somewhat traditional industrial production applications in the framework of Industry 4.0/5.0 to all kinds of novel medical, homecare, servicing, and other societal applications [26].

The formation of a new (transdisciplinary) epistemology is also a concomitant process of the paradigm shift. From different viewpoints, this aims at a unification of the underpinning disciplinary facts, theories, methods, frameworks, and experiences [27]. Another issue is the growing need for sympérasmology, i.e., for the investigation of system-level synthetic knowledge and computational mechanisms. Among others, cognitive engineering needs such means to study and to critically experiment with the artificial problem-solving knowledge and computing resources self-generated and shared by intellectualized systems [28]. Together with the techno-scientific issues mentioned in the previous paragraph, these are growing concerns that cannot be neglected at thinking about NG-CPSs. In addition to intellectualization, socialization, and personalization, the operation of NG-CPSs also features self-awareness, self-adaptation, self-evolution, self-reproduction, and self-supervision [29]. However, in terms of their time scale, these are not long-term objectives. The next generation of CPSs is already around the corner and will enter as soon as the above conceptual blueprints are turned into specific roadmaps of development and deployment.

Acknowledging the changing paradigm, the interest of this paper is in the research and education issues associated with NG-CPSs. Both are concentrating on novel knowledge—research from the viewpoints of its exploration, combination, and consolidation, and education from the viewpoints of its dissemination, synthesis, and operationalization. The extensive contemporary literature suggests that, with a high probability, the traditional research approaches will not be sufficient for providing robust theoretical and technological foundations for the development of NG-CPSs, and that traditional education approaches and didactics will not be adequate to synthesize and operationalize knowledge for these application-and problem-specific systems [30]. However, there seems to be no consensus on what approaches must be practiced and how they can serve the joint interests of 21st-century research and education best. Success with NG-CPSs assumes not less than a globalized techno-informed knowing—practiced by volatile virtual communities which generate knowledge not only for the design and implementation of such systems but also for their embedding and utilization in the fabric of the society [31]. Social embedment of CPSs presumes that their educational practices will be characterized by "reading the words with reading the world" and "seeing hot problems with cold passionate minds."

At the beginning of the 21st century, the organization of the public service of education seems to be influenced by socio-political factors more than by actual scientific progression and professional interests [32]. What was formulated by Giroux, H.A. as a "practice of freedom," education (pedagogy) is expected to gain more attention in this eclectic, if not chaotic century [33]. On the one hand, it should reflect the latest achievements and relations of sciences, technologies, and systems. On the other hand, it should be able to cope with trends, politics, and ideological values. In addition to these conceptual issues, CPS education faces pragmatic ones, such as the ability to blend disciplinary knowledge, capability of thinking in interacting systems, methodology of interest-driven autonomous learning, availability of educators with holistic view/knowledge, practical demonstration of real-life systems, tailoring the preliminary knowledge of students specializing in CPSs, just to mention a few [34]. As for now, two characteristically different fields have been formed by the phenomena of "education for cyber-physical systems" and "cyber-physical systems in education," respectively. These imply that a digitally assisted CPS education is much more than the transfer of structured disciplinary knowledge and that it cannot be started, just terminated too early [35].

3 Articulation of Stakeholders and Knowledge Needs Concerning Next-Generation Cyber-Physical Systems

Design, development, validation, deployment, use, and management of NG-CPSs involve a wide range of stakeholders, consisting of individuals and institutions in various technical and non-technical sectors (Fig. 3). Among others, the stakeholders include (i) academic institutions and their researchers (developing the theoretical foundations and technologies related to NG-CPS), (ii) industrial stakeholders and technology providers who produce technologies, hardware, and software components on industrial/commercial scales, (iii) governments and regulatory bodies that establish and enforce standards and regulations to ensure ethical development and safe operation of CPS, (iv) end-users and operators who define and experience operational requirements specific to application areas, and (v) social entities who are interested in the development trends, addressing societal issues, and moderating and mitigating personal impacts [36]. In line with the increased intellectualization of NG-CPSs, other stakeholders should also be considered, such as (vi) ethics and social science experts who concentrate on ethical issues, social impacts, and human factors related to the putting into practice of CPSs, (vii) installation, maintenance, and support teams who guarantee continuous operation, optimal performance, and troubleshooting problems of CPSs, and (viii) environmental experts who evaluate the potential impact of CPSs on the physical environment and ensure that they do not cause hazard to the environment. Complementing the overview of the influential scientific, technological, and social factors, this inventory of the stakeholders reveals the variety of the knowledge and competencies needed by the NG-CPSs and indicates additional challenges that research and education should be able to cope with [37].

CPSs have been widely and effectively applied in many different areas of our daily lives—they have affected almost everyone in one way or another [38]. From an organizational point of view, the development and deployment of NG-CPSs need the collaboration and expertise of all these diverse (and possibly many other) stakeholders to overcome technical, ethical, regulatory, and societal challenges associated with such complicated systems. Based on the signal-data-information-knowledge-wisdom (SDIKW) integration and abstraction model, systematic studies have been conducted on how data and information should be structured, shared, and used [39]. On the other hand, SDIKW about CPS needs to be ordered and classified according to the different stakeholder groups. This raises the need for conceptual and epistemological frameworks

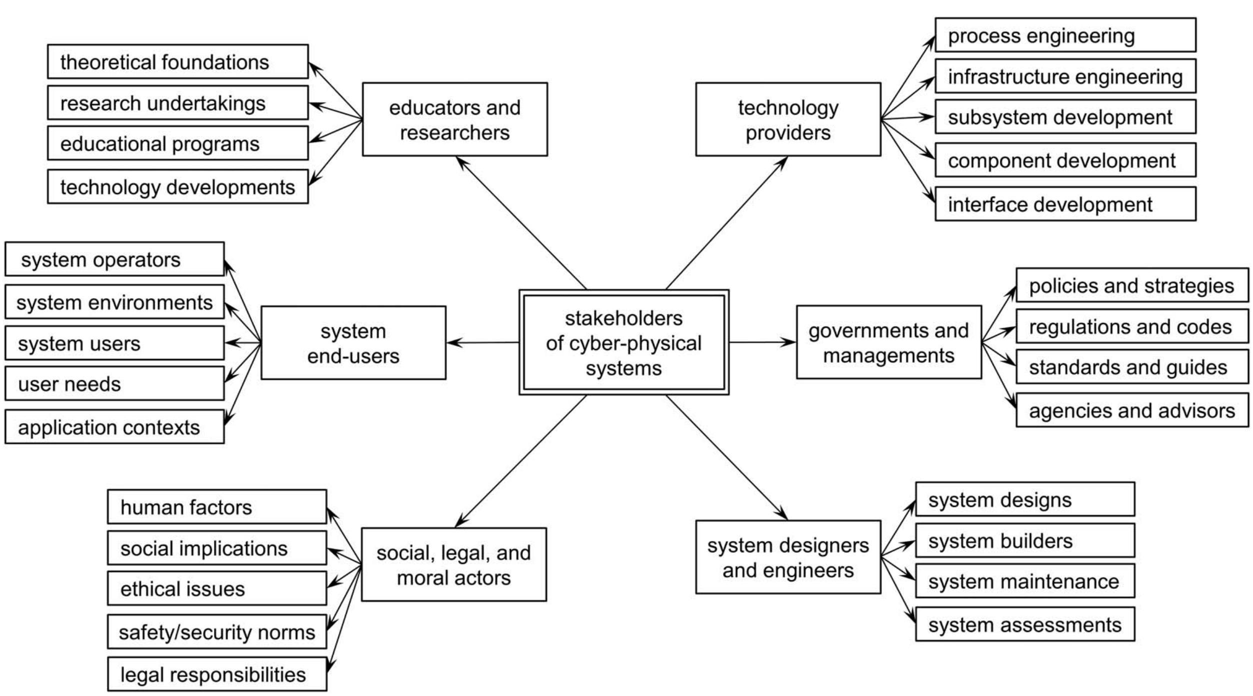

Fig. 3 Stakeholders of CPSs

for knowledge dissemination on various levels for the various stakeholders, as well as packaging cross-disciplinary knowledge in compliance with the demands of each stakeholder group.

First of all, everyone needs to have a basic awareness of what NG-CPSs are, what operations and services they provide, and how they penetrate the physical and cognitive processes of society. The difference between informing, producing, transforming, and hybridized CPSs should be seen. Policymakers and developers of regulations and standards need to have a combined view; they must be able to overview the overall developments and aggregate specific knowledge related to their particular concern domains [40]. The developmental stakeholders of NG-CPS, such as designers, hardware engineers, IT professionals, and data scientists, are expected to have in-depth knowledge of the most important technical aspects of NG-CPS, including integration of analog and digital hardware, control and application software, data and knowledge cyberware, communication protocols, real-time data processing, etc. These stakeholders must have specialized knowledge of (i) the potential risks and cybersecurity, (ii) encryption and secure communications, (iii) safe practices associated with interconnected systems, and (iv) protecting NG-CPSs against incidental cyber threats and vulnerabilities. Stakeholders engaged in cognitive engineering must have data analytics, knowledge representation, machine learning, and other AI-related expertise to be up-to-date and competitive. They also need to have the ability to make inquiries and work creatively across disciplines by collaborating with experts in the above-mentioned fields. These competencies assume a strong understanding of the fundamental concepts of computer science, electronics, control systems, knowledge technologies, communication networks, and autonomous problem-solving [41]. They must also master domain-specific (e.g., healthcare, manufacturing, transportation, etc.) application knowledge and aggregated experiences.

Systems engineering students need to build up competencies in collaborative research, social partnering, technology evaluation, and systems identification, in addition to self-motivated knowledge acquisition and strong problem-solving skills [42]. They also need the ability to collaborate with technical experts, industry stakeholders, and other policymakers to create comprehensive and adaptable regulatory frameworks. But, as Kodály, Z., the famous Hungarian composer said: “the musical education of children must start with that of their parents.” That is, educators are expected to be at least two steps ahead and this can only be achieved by doing research or participating in research teams. In turn, this helps the development of educational programs/courses that recognize the developmental trends and core principles of NG-CPSs [43]. Hands-on experiences with forwarding innovative ideas to practical applications, involvement in prototype and/or real-life implementations, and thinking with the mind of the major stakeholders are indispensable assets for them [44]. These enable them to be successful in out-of-the-box innovation and to be convincing in debates about engineering trade-offs, developer ethics, responsible innovation, competitive business models, and desirable social impacts.

4 Moving Beyond Traditional Systems-Oriented Education and Competence Profile

Both traditional and near-future engineering education face a large number of new challenges, the most influential ones of which are included in the challenge compass shown in Fig. 4. To address these challenges, different institutional policies and pedagogical practices have been operationalized. The different levels and approaches of second-stage education create different views and acquaintance with CPSs, which extend from “puzzling mystery” through “technological mixture” to “inspiring metaphor.” The absence of possibilities to develop holistic systems thinking (worldview) and the lack of involvement in transdisciplinary fundamentals and approaches in educational courses have also been discussed by Ertas et al. [45]. Systems thinking transcends disciplinary boundaries

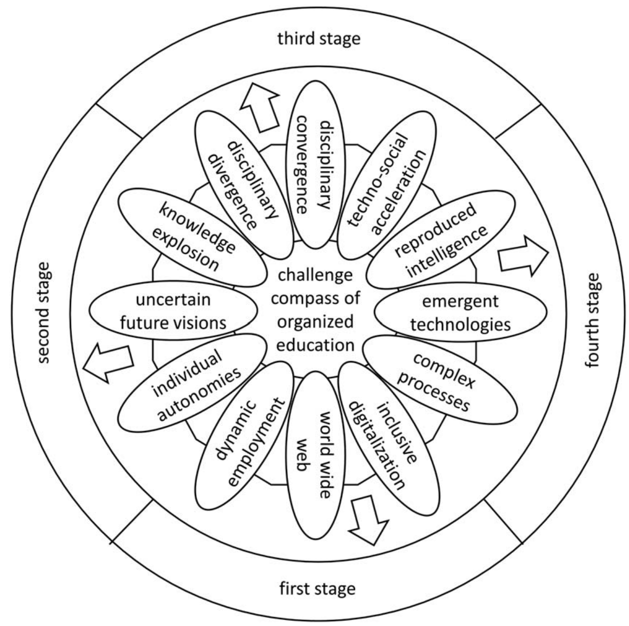

Fig. 4 The present challenge compass of organized engineering education

and needs the ability to holistically view the object of study and integrating knowledge. Though systems-focused educational programs have existed for at least 50 years, they are extremely varied because they (i) focus on traditional (less heterogeneous and complicated) systems, address different challenges, (ii) have been setup under different scientific, technological, social, industrial, business, etc. conditions, (iii) assume different competencies and personal competence profiles, and (iv) fulfill different practical expectations but usually without and dedication to the specificities of CPSs [46]. A taxonomy of systems thinking was proposed by Stave and Hopper to propagate systems thinking in education and to measure the effect of educational efforts in this direction [47]. The taxonomy was derived by analyzing the system dynamics literature and conducting interviews with systems educators.

Pluridisciplinary engineering education programs (e.g., interdisciplinary courses on embedded systems or collaborative humanoid robotics) typically present CPSs as off-springs of the traditional knowledge domains (e.g., mechatronic systems or communication networks). Such courses have a better chance to present the contents through a mixture of disciplines but they do usually not reach that level of holism, in which the engineered systems, their embedding environments, and regular stakeholders are all addressed [48]. On the other hand, emerging post-disciplinary systems education programs—though they are still in their infancy—are striving to develop mental models and professional attitudes of the learners to facilitate their “metaphorical” thinking. This type of thinking sees the real-world problematics and processes through the windows opened by the (present and near future) paradigm of CPSs and asks how worthwhile techno-social progression can be accomplished and how economic and social benefits can be achieved through the deployment of such systems. It is emphasized in the literature that the requirements against such NG-CPS education go beyond those posed for transdisciplinary engineering design education. Though the ontology-based approach, proposed by Butt et al., to find commonalities across the disciplines, seems to be a sensible starting point, it should be revisited due to the changing system paradigms and requirements [49].

Development and implementation of education programs for NG-CPSs are at least as complicated as these systems themselves are and going to be. It should go back to the most fundamental questions of education (i.e., to the trinity of interrelated concerns of engineering education) and ask about (i) a new objective (why to learn?), (ii) a new content (what to learn?), and (iii) a new approach (how to learn?). One practical reason is the large-scale explosion of knowledge that has been going on since the mid-20th century, as a consequence of the simultaneous intensification of organized research activities and almost quasi-open-access dissemination of knowledge. A significant part of the available knowledge is associated with modern technologies and generated by computerization, informatization, and intelligentization. The Internet has become the primary repository of knowledge, offering almost infinite capacities for storage, and almost finite times for retrieval. At the same time, though different by individuals, human cognitive capacities have an upper limit. These are also strong influential factors that education programs for NG-CPSs have to take into consideration [50]. Due to the never-ending need for new scientific, professional, and common knowledge, lifelong learning has been regarded as an indispensable constituent of professional education but without explicit personal strategies and learning methodologies. In addition to human attitudes and behaviors, global problematics priorities also have a large influence on the needed knowledge profiles of individuals [51].

Today's CPSs have reached a complexity level that by far exceeds the intellectual capacity of a single human engineer. Developers and engineers of NG-CPSs will increasingly need to address large-scale systems problems [52]. Consequently, CPS development requires particularly strong soft skills such as social interaction, written and oral communication, and adequate attitudes toward responsibility. They need to be equipped with many new competencies that should receive specific attention in the contexts of education and engineering 5.0. However, authors have claimed that there is still no suitable theory of systematic competence development to date. Pacher et al. discussed aspects of lifelong learning and the individualization of life paths concerning competence-oriented vocational tertiary education and training [53]. In addition to competencies required by collaborative design and collective research, the need for a completely new type of competencies has been also noted. One of them is noesis which, among others, includes abilities such as dynamic awareness, inner wisdom, direct knowing, constructive intuition, analogical association, and implicit understanding [54]. Extremely useful in qualified imagination and reflection, it has a very broad working field from innate and instinct through intuition and intellect to intelligence and wisdom. As a competence, it is extremely important for the creative development of transdisciplinary systems.

There are several explanations for the above phenomenon. One is that, in addition to key engineering competencies, disciplinary competencies are also strongly needed for the profession of CPS engineers. While key competencies are general, disciplinary competencies are specific. Orth classified these needed competencies into four categories: (i) social (e.g., the ability to communicate and collaborate), (ii) personal (e.g., responsibility, self-esteem, leadership), (iii) systematic (e.g., problem-solving and analytical skills), and (iv) general (e.g., project management, information technology) competence [55]. Another explanation is that CPS modules and teaching approaches mainly focus on imparting specific technical knowledge and skills, ignoring the full range of transferable skills required [56].

5 How to Cope With Synergistic Contents and Time Holistic Processes in Systems-Oriented Education

When seen critically, the current landscape of CPS education is like a mosaic with missing bits and pieces. Nevertheless, the contemporary literature seems to be skeptical that traditional engineering competence profiles will indeed work in the NG-CPSs. In the process of formation of genuine CPS education, typically, CPS-specific modules have been introduced into existing computation-intensive system engineering courses [57]. However, an approach appropriate for the "21st century (knowledge-age) education" is supposed to include the social construction of knowledge in specific system contexts as well as collective idea improvement through combining the abstract "idea space" with the physical "maker space." According to Mäkiö et al., the literature reports a skill gap between the expectations of the industry and the competencies of CPS graduates [58]. To close this gap, their paper describes a holistic educational framework (T-CHAT) for teaching CPS engineering at the module level. Though Hairon and Chai emphasized the importance of considering the knowledge of information and communication technologies by the designers of CPS programs, no specific technologies and knowledge have been accounted for by them [59]. Perisic et al. insisted that the helix model of contemporary Industry 5.0 technology can serve as the context of such programs [60].

Students should learn how to constructively interact with members of other disciplines and non-academic fields of practice and how to design and manage inter- and transdisciplinary projects. Carlile posited that (i) knowledge is localized and embedded in practice, (ii) there are semantic boundaries and differences, and (iii) these lead to difficulties in transferring knowledge among actors in multidisciplinary collaborations [61]. The proposed framework integrates the three perspectives of knowledge boundary, namely, (i) the informational (elicitation, pruning, and structuring), (ii) the cultural (practical sharing of meaning), and (iii) the political (establishing and coordinating mutual interests) perspectives. While this framework makes sense in the case of organizational knowledge, it needs further research to explore what it concretely means concerning knowledge for CPSs and their synthetic knowledge. Furthermore, it is emphasized by many scholars that a re-consideration of the pedagogical doctrine is also strongly needed.

Two intertwined challenges for the education of NG-CPSs are the support of (i) holistic thinking over a multitude of disciplinary boundaries and manifestations of systems and (ii) building the attitude of holistic viewing and practicing. The latter is not only a human ability but also a deeply rooted and long-time-built mental model whose development needs personal inspiration and proper didactic approaches. It has been found that holistic thinking can be supported by a kind of "reverse engineering" of professional mentality and intellect. What it means in practice is that instead of beginning with various chunks of monodisciplinary knowledge, education should start with the expected results, i.e., from existing (transparent, as well as complicated) systems, which reflect (i) disciplinary convergence, (ii) functional/architectural compositionality, (iii) successful integration of knowledge and technologies, and (iv) functionalities toward novel system realizations. In other words, it means a comprehensive replacement of the traditional bottom-up approach (BUA) of content and process organization by a top-down approach (TDA) which presents the essence of target systems first and then explains how they are realized from conceptual, technological, intellectualization, operational, and interaction viewpoints. The above-mentioned overall strategies of educational content and process organization also influence the obtainable professional competencies about NG-CPSs.

Being analytic, BUA is known to deal with these according to the philosophy of epistemological reductionism (the view that systems can be explained by considering their components) [62]. Pursuing transdisciplinarity, TDA projects out from epistemological holism (the view that the whole of a system must be analyzed rather than simply its components) [63]. Figure 5 compares the main conceptual elements of the two overall strategies. In practice, the reductionist view implies a bottom-up education organization and knowledge transfer. In this case, systems are explained by considering their constituents (monodisciplinary bodies of knowledge, typical systems components and solutions, system comprehension competencies, and system implementation abilities). Driven by an integrative view, holistic education organization and knowledge transfer set out from overall cases/examples of systems, interpreting their inputs and outputs, the general/specific transformational operations, and the interactions with the application environment and the target stakeholders. This approach projects the whole of the system to the constituents, progressing from the system paradigms and models,

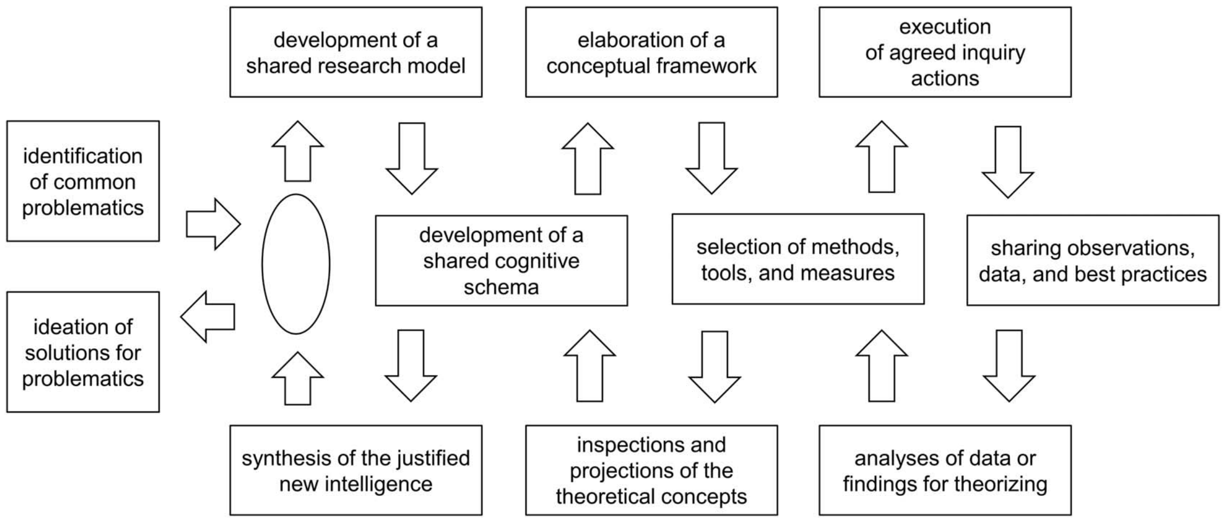

Fig. 5 A simplified procedural flow of transdisciplinary research

through the architectural, functional, and implementation elements, the supporting solution concepts, technologies, and methodologies to the invoked contextualized disciplinary knowledge. The top-down educational strategy is a vivid alternative to the bottom-up approach but not a replacement for it. It may offer many advantages in the case of learning complicated CPSs but needs a high-level background (disciplinary knowledge) and attitude toward holistic systems thinking, as opposed to analytic thinking. The synthesis of knowledge indispensable for its implementation necessitates effective methods [64].

As a move toward holism, Bereiter and Scardamalia introduced the concept of "knowledge-building" as a new form of constructivism [65]. They proposed a framework for building the intellectual capacities needed to successfully participate in expert knowledge construction processes through staged apprenticeship in the discipline's ways of developing knowledge. Because of the reason that design and other creative activities are strong knowledge integrators, this concept deserves attention also in the context of CPS education. A comparable alternative is the concept of the teaching factory that provides an environment for close collaboration with experts of different knowledge and backgrounds and the use of both emerging and industry-accepted digital technologies [66]. Another proposal, the Education 4.0 framework, actively involves the trainees in realistic simulations that increase the perception of complexity, heterogeneity, and novelties [67]. As analyzed more than 25 years ago, higher education needs to contribute more effectively to the improvement of the performance of society and the economy [68].

No one should expect that the top-down approach can be realized by one course. It needs harmonization of educational programs over the first, second, and third stages of organized (institutional) engineering education [69]. At the same time, education planners are supposed to acknowledge its didactical affordances for autonomous lifelong learning, in particular, with a view to the changing system paradigms and the proliferation of metaverses [70]. Students do not need to learn all topics of the foundational disciplines in detail. Instead, they can concentrate on understanding the key relationships knowledge, technologies, and systems. Thus, the learning outcomes are expected according to the priorities of identification of problematics, understanding innovation, pluridisciplinary conceptualization, logical reasoning, decision making, and synthesizing and application of skills. However, there are still serious problems in acquiring all these skills [71]. Innovative education and systematic inquiry are to be methodologically integrated both at the program level and at the course level [72]. Problem-solving-focused education courses and operative research processes should be carried out with multi-stakeholder and public participation, for instance, based on living laboratory and science for citizen approaches [73].

6 Limitations of Mono- and Interdisciplinary Research

Mode 1 research focuses on new knowledge as defined by a set of peers within a particular discipline, while mode 2 research focuses on new values for society and propagates academic activities that are cross-disciplinary, outward-facing, and problem-solving without a well-defined body or peers. Outward-facing mode-2 science does not overwrite but complements inward-facing mode 1 science. It has been learned that they, in combination, provide a better platform for concurrent inquiries in complex natural phenomena and finding solutions for complicated problematics of today and tomorrow. While the principles of mode 1 science have been crystallized over the centuries, the principles of mode 2 science are in a premature (inception) phase and only partially known not only for the broader society but also for academia and the scientific bodies. This relative unknowingness concerns not only the epistemologically different knowledge but also the different conducts of scientific research in complicated problematics. The latter assumes not only deviation from the so-called "voluntarist academic tradition" approach but also needs a comprehensive conceptual and procedural framing toward so-called "transdisciplinary epistemic communities" [74]. As these descriptive phrases indicate, a shift from individual investigators working in teams to heterarchical collectives of research preparers and elaborators is expected to happen.

The disciplinary complexification accommodated in emerging problematics casts a strong light on the limitations of the traditional research approaches. Combined with the usual immediacy of the need for underpinning research results, the above complexities emphasize the need for doing research by multi-professional communities instead of individual investigators. Besides, it is straightforward to involve industrial, social, and even political stakeholders in addressing industrially, socially, or commercially created problematics and the concomitant organizational and management issues. The overall goal of mode-2 science is to achieve higher impact, rather than higher insights [75]. Nevertheless, arriving suddenly and unprepared at the gate of mode 2 science, the lack of proper research methodological frameworks, models, and processes has been recognized by many researchers. One of them is the unavoidable necessity for forerunning and subsequent knowledge synthesis in the case of broadly based collective research approaches (Fig. 6). Another one is the unsophisticatedness of the current research methodological reality of doing research for

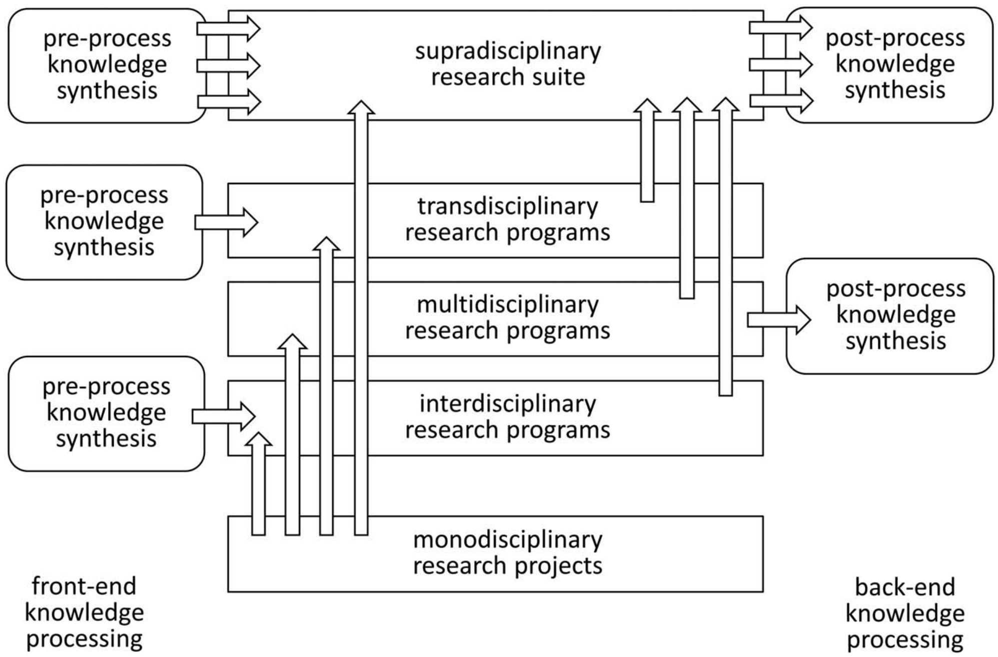

Fig. 6 The epistemic-logical framework of supradisciplinary research

intellectualized, socialized, and personalized CPSs. Obviously, this issue goes in hand not only with the exploration of the deficiencies of the current conducts of research but also with changing the orientation of value-generation of science. Even a large part of applied research is still characterized by gaining deep insights, instead of achieving broad impacts expected from complex NG-CPSs. There is no causal link between research excellence and high-impact research.

There have been various methods of knowledge synthesis studied and applied such as (i) outcome of coadunatedly executed collective inquiries, knowledge integration through shared model development, (ii) integration through common conceptual frame development, (iii) cross-boundary development of methods, (iv) adapting existing multi-purpose tools, (v) integrative semantic analysis of findings, (vi) axiom-based blending of chunks of knowledge, (vii) integration of collaborative system development, (viii) semantic/conceptual integration through joint publications, (ix) iterative refinement and blending of outcomes, (x) integration by joint project specification, and (xi) formulation of multi-aspect research questions and hypothesis. A simplified procedural flow of transdisciplinary research is shown in Fig. 7. It is also important to see the paradox that is hiding behind doing transdisciplinary research and having individual knowledge because the former is supposed to be synthesized and comprehensive, whereas the latter is known to be scoped and restricted. Academics in research institutions are supposed to describe the impact of their research outside academia in detail also for the social stakeholders, and not only for the industrial partners.

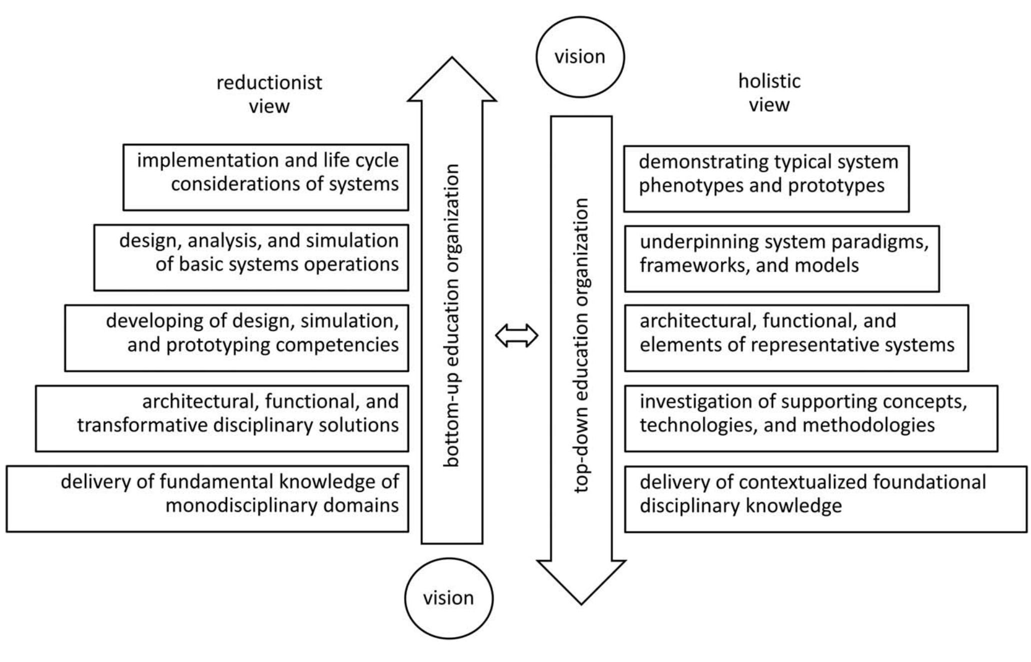

Fig. 7 The two major strategies of the organization of educational content and competencies

A recent development is a growing interest in researching the para-functional capabilities of CPSs. Sentience (like in sentient robots) for instance has been found necessary for the development of next-generation socialized cyber-physical systems. This also concerns transdisciplinary studies of having intuition, deriving conjectures, and reasoning with abstractions. These are as challenging in the theoretical realm, as prototyping is in the practical realm. Though prototyping is one of the most effective ways of exploring new systems concepts and assessing them from practical contexts, it is challenging when it comes to using high-fidelity physical prototypes in research and education for and in distributed and multilevel CPSSs [76]. The problem originates not in the difficulty of translating the prototypes into theoretical knowledge but in covering the costs of building, testing, and recycling large-scale prototypes. This is also interwoven with the rapid material, energy, information, and knowledge technological developments. For instance, organic substances are used in the physical domain as materials for physical constituents in sub-millimeter-sized and human-body-conform analog hardware design and provisioning.

Research in digital twins (DT) is one of the most emphasized activities in the cyber domain. Based on the initial specification of the Digital Engineering Integration Committee of the American Institute of Aeronautics and Astronautics (AIAA), various definitions have been proposed [77]. The core of many of them is that digital twinsareset of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems) [78]. Having a predictive capability, these interrelated algorithmic constructs (i) are dynamically updated with data from its physical twin, (ii) support (quasi) real-time bidirectional interaction between the virtual and the physical constituents, (iii) inform human-in-the-loops decisions concerning operational processes, and (iv) enable fit-for-purpose-fidelity and uncertainty quantification. This research addresses research questions that concern monodisciplinary, interdisciplinary, or multidisciplinary knowledge gaps (e.g., advanced hybrid modeling approaches of data-driven and model-driven synergistic digital twin formulations). However, research questions involving human and social aspects (such as using DTs in medical applications) raise the need for transdisciplinary research designs and require supradisciplinary research organization following an integrated research agenda [79]. This is also strongly demanded by the growing synergy among the system constituents as forecasted by Singh et al. [80]. Such an approach cannot be missed when the research is organized around research models having knowledge gaps in meta-management, ethics, apobetics, privacy, security, and sustainability.

7 Specific Research Issues and Approaches Concerning Next-Generation Cyber-physical Systems

The literature seems to be limited in terms of overviews of the knowledge gaps and the high-priority research domains related to current and next-generation CPSs as well as about the research methods and techniques dedicated to them. At the same time, the rapid paradigmatic evolution, disciplinary complexification, and technological heterogeneity of NG-CPSs bring in many specific research issues [80]. Some of these have already been touched upon from other viewpoints in the preceding sections. For instance, the paramount importance of cross-disciplinary integration of knowledge related to the development and integration of analog and digital hardware, control and application software, data and knowledge cyberware, communication protocols, real-time data processing, etc. has been emphasized from the aspect of the mindset of developmental stakeholders of NG-CPS, who are also supposed to share knowledge from related domains of human, behavioral, social, economic, and legal sciences. As CPSs penetrate society, sufficient knowledge about the principles of Society 5.0, social relations, business processes, region-dependent lifestyles, and even ways of human thinking will be needed. While it is easier to recognize what sort of knowledge implications certain types of CPSs go together with, it is more difficult to explore missing chunks of knowledge in research and to consolidate new insights with a view to the knowledge carried by the developmental stakeholders.

Contrary to the importance of the above, Wan et al. claimed that the inquiry into the theoretical fundamentals must be of high priority [81,82]. They identified (i) energy management for both computing and non-computing components, (ii) network performance and security, (iii) data transmission and management, (iv) model-based design and engineering, (v) control techniques, and (vi) system resource allocation as other important domains of inquiry a decade ago. As core inquiry domains in the context of cyber-physical systems of systems, Engell et al. identified (i) robust system architectures and decision structures, (ii) self-organization and emergent behaviors, (iii) real-time monitoring and fault management, (iv) adaptation and integration of augmenting components, (v) humans-inclusive collaborative decision making, and (vi) trust building in large distributed systems [83]. The current manifestations of cyber-physical-social-human systems in the industry [84], the built environment [85], and social robotics [86] reveal a large number of other research issues that need to be addressed. For instance, multidisciplinary studies require a thoughtful approach to assembling the team, assigning roles and responsibilities, and allocating research tasks to reduce potential conflicts [87]. On the other hand, exploring the approaches of creating shared conceptual spaces facilitates the transdisciplinary innovation of NG-CPSs [88].

NG-CPS will have a range of experiential and potential influences on our daily lives and lifestyles. On the one hand, the concrete range of influences should be explored about the features of the different systems to be able to tailor them [89]. On the other hand, approaches to maximizing the positive trends and effects and minimizing the negative ones should be found. These call both for a continuous investigation of the new technology trends and implications of systems on society, and the development of social regulations, policies, and standards according to the needs of society [90]. Though addressed frequently in research, security threats and safety solutions of CPSs are typically investigated in monodisciplinary and interdisciplinary studies [91]. It seems that the progression of research is not the same in the different fields of CPSs. Medical [92], healthcare [93], production [94], transportation [95], and energy [96] CPSs are more intensively studied than others such as home care, horticulture, and water management but most of the studies are monodisciplinary or interdisciplinary at most.

8 Some Thoughts About Including Artificial Intelligence in Cyber-physical Systems Education

Cognitive design and engineering of NG-CPSs involve the development of application problem-solving-specific computational algorithms/mechanisms as well as re(use) of problem-solving methods, systems, tools, and other resources (e.g., knowledge repositories) which have been generated by research in AI. That is why the questions posed by the peer reviewers and the two additional issues they suggested to address in this paper are important and should be considered. Taking their points, we present our view in this section. The first point is that it would be valuable for the readers of JCISE to have a discussion about the role of AI in terms of education for NG-CPSs and how AI can be integrated into the existing framework of education without having to build a completely new major. As a context, it was mentioned that the current education system still heavily focuses on traditional approaches, and AI-fostered education for such purposes is still under-developed. On the other hand, the past achievements, likewise the recent advances of generative AI (such as GPT-4 Turbo, Liama 2, Claude 2, or PaLM 2, having billions of text coding parameters and thousands of tokens in their context windows), may affect the development of NG-CPSs [97]. The other suggestion was to further clarify the ethical considerations tied to AI and explore how NG-CPS curricula can incorporate modules dedicated to addressing these pressing concerns. Our immediate reflection is that both issues (i) are extremely important to be dealt with right now, (ii) represent an enormous complexity that is complicated to address, (iii) have emerged recently—therefore, there are still significant knowledge gaps and conceptual frameworks missing, (iv) are rapidly developing, and new findings and implementations are mushrooming, and (v) should be considered in specific contexts, which implies that looking for solutions that fit for all may not be possible.

Forgetting about "artificial general intelligence" or "artificial super intelligence," concerning the above-mentioned complexity, we must see that the field of knowing, doing, and making referred to as "artificial narrow intelligence" (ANI) is not one holistic thing but a vague and loose composition of different interest domains and attainments. Our recent survey tried to make an account of and impose an order on these domains. Based on what they deal with, they have been classified into six categories, namely (i) foundations (e.g., intelligence theories, artificial brain, and computational intelligence), (ii) perception (e.g., speech understanding, artificial vision, and image synthesis), (iii) cognition (e.g., symbolic reasoning, deep learning, and serious games), (iv) animation (e.g., humanoid robots, robot swarms, and micro/nano-robotics), (v) emotion (e.g., artificial feelings, affective computing, and emotional modulation), and (vi) assistance (e.g., automated translators, expert systems, and answering/recommendation systems). It is important to consider this wide variety in projecting AI to NG-CPSs (from both educational and engineering perspectives), in particular for the reason that the latter systems also show a wide variety in terms of their functional objectives, addressed real-life problems, computational resources, implementations, and so forth. The most relevant subset of the AI enablers should be allocated to each specific family of NG-CPSs [98]. This is the principle that should be adopted and operationalized in educational programs and courses concerning NG-CPSs. As choices are made on the family of CPSs to be taught in the planning phase of educational programs, decisions are to be made about what knowledge and resource elements of the six AI enabler categories must be dealt with, also considering their evolutionary trajectories [99].

Though there are different views on the reproduction of human intelligence (Fig. 8), AI in education is a currently proliferating and culminating phenomenon, which, together with computational support of semantic knowledge synthesis, has created a new hype and promises [100]. While the opportunities provided by the newly emerged AI means should be explored, extensively tested, and made deployable, overemphasizing their capabilities and potential for the disfavor of the other well-established technologies must be avoided. Though expected to manifest as a short-term technology push, it is not yet known what extent of impact and revolutionary changes can be expected from the results of constructive and generative AI research [101]. Gudoniene et al. identified several benefits of using AI in education such as (i) organized information, (ii) personalized learning, (iii) serving learners with special needs, (iv) immersive learning, (v) intelligent tutorial systems, (vi) adaptive group formation, (vii) facilitation by examples, (viii) intelligent moderation and virtual reality learning, (ix) software-based assessment, (x) machine translation and interpretation, and (xii) attractive learning environment [102]. However, it also shaped possible threats, such as the extinction of the educational personnel's fears of risk and the weakening of the personality development relationship between teacher and students, as discussed by Humble and Mozelius [103].

Nonetheless, the issues of the sudden emergence of a wide variety of specific AI tools and the persistent lack of educational AI application policies and frameworks have also been addressed [104]. Some useful conclusions about the possible future of ANI-supported medical education have been provided by Eysenbach [105]. He reported on an example of an extensive interviewing ChatGPT, using it to simulate a virtual patient–doctor communication, and to generate quizzes for medical students, and derived. He concluded that hallucination (i.e., a confident response by an AI system that does not seem to be justified by its training data) is a major problem in large language models that may occur in educational contexts. This phenomenon may also be present in the use of generative image application tools, such as stable diffusion or Dall-E, to produce illustrative images from textual descriptions or verbal narrations [106]. The results of the work of Ray seem to confirm the above findings and call attention to several ethical issues in the existing computing domain and how ChatGPT can invoke challenges to such a notion [107].

A dominant trend is to study AI in context, which is also regarded as an important factor in the education of this type of systems [108]. One of the most important contexts is ethics. Though most of the former studies addressed AI-related ethics (norms and codes) from a general engineering perspective, some recent publications concentrated on the ethics of using the latest ANI tools. For instance, Sidiropoulos and Anagnostopoulos posited that AI technologies have reached extraordinary levels and is now capable not only of retrieving and providing simple information but also of critical thinking to an extent [109]. Therefore, they attempted to identify the accompanying major challenges and the ethical issues that arise from using AI technologies in various applications, such as education, scientific research, and caretaking. Likewise, Kirova et al. focused on ethical issues related to the era of generative

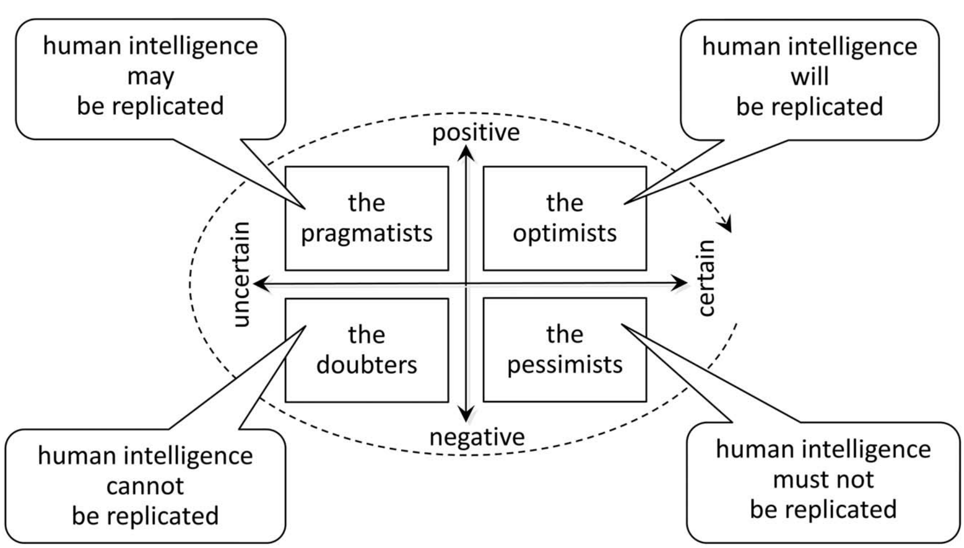

Fig. 8 Different views on the reproduction of human intelligence

AI [110], while Gill et al. provided insight in the transformative effects of ChatGPT and other AI chatbots on modern education [111]. Human privacy preservation has been claimed as an important aspect of normative consideration and Rivadeneira et al. proposed a unified privacy-preserving model with AI [112]. Johri et al. also highlighted some new challenges posed by generative AI, for instance, (i) AI-aided plagiarism, (ii) deskilling and replacement, (iii) the imperative for human augmentation and capacity enhancement, (iv) fair use of AI-generated content, and (v) equity and accessibility [113]. They emphasized that (i) the scalability and complexity of these applications require a deliberate effort within the educational community to minimize harm and promote responsible use, (ii) it is necessary to extend the existing ethical guidelines to meet new challenges posed by generative AI, and (iii) it is also important to mitigate the risks and maximize the positive impact of generative AI in engineering education by striving for transparency, accountability, privacy, and human-centeredness.

9 Findings, Reflections, and Suggested Actions

Answering the question stated in the main title is relatively easy based on our exploratory analysis. No, we do not know the absolute solution concerning either the "what" or the "how." In addition, it would be unfair to claim that we have managed to find out what the best possible alternative can be. As the literature informs, many attempts have been made but most of them are just about finding something that works for a given purpose, in a specific context, and for the time being. The published particular solutions do not converge, and cannot be synthesized into one overall approach. The main reason is the unsettled circumstances and the concurrent changes under which CPS education is supposed to take place. Our explorative study disclosed and analyzed the most influential factors and trends that extend, among others, from the rapid proliferation of CPSs, through the rising need for transdisciplinary approaches, to the inseparability of research and education. In the background are the drastically changing views on what neo-post-modern science is about and what ways this new reality can be dealt with. In addition, the paradigm of cyber-physical systems is going through a metamorphosis, together with the alterations of the social environments and demands. Our concrete findings are:

- We are in the era of a not-yet-culminated neo-post-modern contemplation of science which simultaneously challenges the classical foundational ideas and promises a new post-disciplinary reality. Concerning these, it has to be taken into account that we are probably still closer to its beginning than to its finish and that it is just the tip of the iceberg that the literature reflects. The real depth of this revolutionary progression cannot even be estimated or foreseen but it is well known if the iceberg melts (i.e., the progression escalates uncontrolled), the water levels (i.e., the uncertainty likely grows).
- The dialectics of scientific/disciplinary convergence and divergence, in combination with the many forms of integration of new technologies, creates new potentials for CPS development. The current stage of the evolution goes together with a remarkable change in the system paradigm of CPSs and is characterized by highly intellectualized, socialized, and personalized systems which form clusters of self-organizing systems of systems and serve as responsible autonomous systems. Their deployment has significant social consequences which manifest in rather different forms in the different fields.
- The knowledge underpinning the recently implemented systems extends concurrently to the social space, the human space, and the cognitive space, in addition to the physical and cyberspace. Based on this, they can offer not only a wide spectrum of functionalities but also implement abilities such as self-adaptation, self-evolution, and self-reproduction. These features have far-reaching influence both on research in and education of CPSs.
- Though virtual experiences can be created with moderate efforts, gaining experiences with tangible (operational) prototyping of large-scale cyber-physical systems bumps into restrictions due to the usual complicatedness, incurred costs, accessibility of resources, and time limitations and constraints.
- An educational approach appropriate for the knowledge age of the 21st century is supposed to include (i) social construction of knowledge in specific system contexts, (ii) collective idea improvement through combining the abstract "idea space" with the physical "maker space," and (iii) overbridging skill gaps between expectations of industry and competencies of CPS graduates.
- Both the traditional and the near-future engineering education face a large number of new challenges. Probably the most dominant will be the still evolving and debated AI technologies and systems. Therefore, developers of education programs for NG-CPSs should go back to the most fundamental questions of education (i.e., to the trinity of interrelated concerns of engineering education) and ask about (i) a new objective (why to learn?), (ii) a new content (what to learn?), and (iii) a new approach (how to learn?).

Consequently, our propositions are as follows:

- Both education and research must consider the latest results of complexity science whose main objectives are: (i) getting cross-disciplinary insights into complex systems, (ii) explaining emergent structures and self-organization, (iii) generating effective abstractions and models, and (iv) providing control methods for complex systems.
- Design, development, validation, deployment, use, and management of NG-CPSs involve a wide range of individual and institutional stakeholders, having largely different objectives, interests, and backgrounds. Education of CPSs should consider these and offer sufficiently articulated educational programs. This raises the need for conceptual and epistemological frameworks dedicated to knowledge dissemination on various levels for the various stakeholders.
- NG-CPS education can in principle be organized according to the principles of bottom-up and top-down knowledge structuring and process organization. The latter allows (i) holistic thinking over a multitude of disciplinary boundaries and manifestations of systems and (ii) building the attitude of holistic viewing and practicing. In practice, it means that instead of starting with various chunks of monodisciplinary knowledge, education should project out from the desired results, i.e., from existing or conceived representative systems.
- The second and third stages of traditional engineering education are supposed to create a strong coupling between research and education (learning by exploring), between design and education (creating for learning), and between research and design (exploring by creating). This triple relationship also applies to CPS education. Graduate and postgraduate students are expected to get engaged in large, ad hoc teams and to conduct systems-related research in formal ways to gain multidisciplinary research literacy.
- The current research methodological reality is deemed to be insufficient for doing research in and for intellectualized, socialized, and personalized CPSs. Even a large part of applied research is still characterized by gaining deep insights, instead of achieving broad impacts expected from complex NG-CPSs. There is no causal link between research excellence and high-impact research.
- Supradisciplinary research organization in the field of CPSs calls for a continuous investigation of the new technology trends and implications of systems on society, and the development of social regulations, policies, and standards according to the needs of society. It seems to be equally challenging to recognize what sort of transdisciplinary knowledge demands certain types of CPSs have and to explore the missing chunk

of knowledge by doing transdisciplinary research collectively, including the developmental stakeholders.

The main methodological conclusion of the authors is that due to the continuing scientific, technological, and social changes, research and education must also be continuously changing. Instead of well-founded frameworks, pre-defined scenarios, and fixed objectives, (i) versatility, (ii) up-to-datedness, and (iii) resourcefulness are needed for all actors. In addition, prognostic systems thinking, transdisciplinary inquiries, and autonomous learning should go hand in hand.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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