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Foundations for Post-Disciplinary and Transdisciplinary Education for Next-Generation Cyber-Physical Systems

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ABSTRACT

Post-disciplinary and transdisciplinary knowledge synthesis facilitates extensive intellectualization, socialization, personalization, and naturalization of next-generation cyber-physical systems (NG-CPSs). However, it makes learning and teaching NG-CPSs more challenging and calls for new educational methods. These challenges arise because (i) conceptual familiarization with these systems must start in basic education for attitudinal reasons, (ii) proficiency in technologies and system development must continue through undergraduate, graduate, and postgraduate levels, and (iii) keeping pace with the evolution of NG-CPSs requires lifelong learning skills and efforts. The goal of the research was to critically review the current state of the art, reveal the related epistemological and computational issues, examine pedagogical and andragogical concepts, and propose specific approaches based on innovative mental and procedural models. A thorough and systematic literature review was conducted, guided by five main research questions. After clarifying the specific objectives, this treatise, rendered as an argumentative position paper, offers a notional clarification to support a consistent interpretation of foundational concepts and definitions, and their relationships. This is necessary due to the prevailing confusing terminology and frequent differences in concept interpretation. The core features and manifestations of the system paradigm of CPSs are analyzed, and a conceptual model illustrating the strands of paradigmatic evolution of CPSs is proposed. Finally, an overview of the likely operations and characteristics of NG-CPSs is provided. The knowledge components mentioned

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above are vital not only for informing readers about the state of the art in CPSs but also for establishing a solid foundation for pedagogical advancements.

Keywords: Fundamental Concepts; Engineering Education; Cyber-Physical Systems; Next-Generation Systems; Artificial Intelligence; System Manifestations

1. Introduction and Setting the Stage

1.1. Background, Focus, and Goals of the Study

Every year, hundreds, if not thousands, of publications disseminate information about the emergence, overall progress, and current state of cyber-physical systems (CPSs), as well as specific research and development results[1]. Initially, these systems were regarded as technological enablers and drivers of industrial, agricultural, transportation, and so forth, activities, but they also penetrated everyday applications over the years[2]. Typical non-industrial CPSs include (i) stroke rehabilitation systems, (ii) dementia monitoring and assistance systems, (iii) emergent incident management systems, (iv) home care and service supporting systems, (v) autonomous vehicle fleet steering and parking systems, (vi) personalized and adaptive education systems, (vii) medical intervention/treatment support systems, (viii) sport performance enhancement systems, (ix) children's ability development systems, etc. Their intellectualization, socialization, personalization, and naturalization have created possibilities for radically new functionalities and applications[3].

These evolving properties are paving the way for NG-CPSs, which are already in the limelight of exploratory research and experimental development. System knowledge related to them integrates physical principles, engineering constraints, cognitive resources, human practices, organizational rules, economic realities, cultural meanings, and ethical boundaries. Engineering knowledge nurturing them is becoming reflexive, normative, adaptive, and situated. The latest philosophy is that engineers must let their knowledge of how NG-CPSs manifest co-evolve with society's understanding of probabilities and possibilities over time. That is, the object of knowledge itself is co-produced with society. This transforms the research and development of CPSs into a continuous collective learning process about how humans and systems can and should coexist. This mentality radically deviates from the current practice of 'stakeholders are consulted' and 'users giving feedback' and moves towards a practice in which civic society engages in co-creation and epistemic co-authorship across the entire lifecycle of such systems.

NG-CPSs will be relying on post-disciplinary and transdisciplinary bodies of knowledge. Society and science will co-create what the NG-CPSs are, what they are for, and how we know if they are proper. They will necessitate an intensive synthesis of knowledge in research and a holistic acquisition of knowledge within education and system development. As much as CPSs' education is concerned, it needs novel and effective pedagogical approaches as well as knowledge synthesizing systems. Elevating the efficiency of education necessitates reconsidering the current mental models, governing strategies, institutional learning programs, and de-institutionalized forms of education, such as autonomous and life-long learning. In addition to increasing functional sophistication by integrating the latest technologies and tailoring them to demands, systems-oriented engineering education (SOEE) should facilitate the understanding of the complex interactions among technical, social, and environmental elements in the solution design process, and be sensitive to sustainable development goals and contexts[4]. Furthermore, it should be instrumental to fulfilling the generic system expectations, such as system safety, security, assurance, reliability, sustenance, maintenance, resource allocation, powering, and networking, even if NG-CPSs manifest as self-adapting and self-evolving systems[5].

Dealing with the topic circumscribed by the title is challenging due to its multifaceted nature (the variety of domains and concepts involved) and the recent radical changes in theoretical research and practical innovation. The knowledge associated with mature transdisciplinary CPSs engineering and education programs will include (i) design principles that evolve with society, (ii) trust models grounded in lived practice, (iii) governance built into architecture, (iv) users as co-designers of meaning, not just interfaces, (v) intellect that stays alive after deployment, (vi) safety concepts that include social failure modes, and (vii) ethics that serve as operational, not abstract. An all-inclusive treatment is made difficult not only by scientific convergence, technology integration, and knowledge synthesis that have taken place over the last two decades, but also by the unsettled terminology and multiple differing definitions. Notwithstanding, the goal of the study was multifold. It tried to cover the status, approaches, and probabilities of education for post-disciplinary and transdisciplinary CPSs, considering both pedagogical and andragogical issues and possibilities.

On the one hand, this paper presents a comprehensive and critical overview of the state of education in the fast-changing field of CPSs. It concentrates on the challenges and possibilities of moving towards post-disciplinary (PDEE) and transdisciplinary engineering education (TDEE) of NG-CPSs. It is a rapidly increasing real-life issue, requiring genuine thoughts to address uncertainty and controversy. On the other hand, it is hoped that this work sheds light on influential theoretical, methodological, and practical innovations, despite the lack of uniform interpretation and general agreement on the essence of the challenges and the blueprint for feasible, lasting solutions. The paper also elaborates on the most important pedagogical and andragogical issues, and proposes specific approaches based on novel mental and procedural models. The arguable opinion and the underpinning arguments are built not only upon factual evidence but also on the knowledge and experiences aggregated by the author over the years. He intended to clarify his conceptual position, underpin it with other evidence from well-researched sources, or contrast it with seminal works published in contemporary literature.

1.2. Guiding Research Questions

The processing of literature and concepts has been guided by five general research questions.

1. What foundational concepts, knowledge domains, and bodies of knowledge are deemed relevant to CPSs from educational perspectives?
2. What does the paradigmatic evolution of CPSs mean, and how will NG-CPSs manifest?
3. What are the recent conceptual innovations and milestone developments in engineering education concerning systems education?
4. What are the major trends of pedagogic and andragogic progression that are relevant for learning NG-CPSs?
5. What can be recommended for follow-up research, development, and practical activities considering the current uncertainties and emergencies?

Based on these research questions, the keyword clusters shown in **Table 1** have been constructed. The keywords mentioned in the clusters were used to generate composite search terms. More than 120 such search terms (semantically meaningful keyword combinations) have been used in surveying the publications within the given time window.

Table 1. Keyword clusters and entities used in the systematic publication retrieval.

Cluster of Keywords	Foundations of Cyber-Physical Systems	Paradigmatic Evolution of Cyber-Physical Systems	Innovative Learning and Teaching Practices for CPSs	Learning of and by the Next Generation CPSs	Foreseeable Future of Cyber-Physical Systems
CPSs	concepts	paradigms	teaching	institutions	missions
	definitions	features	learning	programs	visions
	frameworks	trends	education	courses	strategies
	models	smart	innovative	contents	policies
	components	smartification	didactics	contexts	roadmaps
	principles	intellect	pedagogy	monodisciplinary	research
	manifestations	intellectualization	andragogy	interdisciplinary	development
	knowledge	intelligence	heutagogy	cross-disciplinary	innovation
	technologies	intelligent	intra-mural	post-disciplinary	problematics
	languages	intellectualization	extra-mural	transdisciplinary	phenomena
	generations	human	online	agents	supra-disciplinarity
	functions	social	autonomous	environments	embodied AI
	architectures	natural	lifelong	AI-enabled	agentic AI
	energies	eco-system	assessment	relationships	organic AI
	costs	next generation	epistemology	apobetics	quantum AI
	users	ontology	methodology		cyborgs
	deployments				submicron-robotics

1.3. Research Approach

The research underpinning this position paper included two strands of activities. One of them is the author's multi-year research in education for CPSs that focused on post-disciplinary and transdisciplinary research and education approaches. Another is a systematic literature survey conducted to explore the state of the art. The reported facts and conceptual findings identified in contemporary literature have been combined or contrasted with the author's personal view and claims. This is exactly why this paper has not been conceptualized as a state-of-the-art survey paper, which tries to present comprehensively what is out there, but as an academic position paper. It is important to emphasize that the paper is not a systematic survey/review paper that would benefit from the structured approach of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020), its four-phase study selection process, and the 27-item checklist. Though certain elements of this approach are present, what has not been operationalized here are its targeted comprehensiveness and well-argued selection mechanism. The Web of Science, Scopus, Google Scholar, and Research Gate repositories have been used to find publications matching the systematically generated composite search terms. Only seminal papers reporting on supporting or opposing (agreeable or disagreeable) opinions have been selected from the investigated professional literature from 2010 to 2025. Nevertheless, the empirical and theoretical publications included in the list of references hint at the breadth and depth of the study. Although not providing an exhaustive overview of the overall progression achieved so far, each of the purposefully chosen publications makes, in one way or another, a professional contribution to systems education in the context of this paper.

As is known, a position paper is a purpose-determined formal contribution, supposed to present a detailed argument on a specific issue, by articulating the author's professional position and backing it with evidence, literature references, past research findings, and logical reasoning[6]. Its primary purpose is to (i) clarify an expert position (insightfully articulate a clear and concise stance on an issue), (ii) persuade readership (convince by presenting compelling arguments and evidence), (iii) demonstrate current state and knowledge (present sufficient depth of understanding and explore a complicated issue), and (iv) promote constructive and critical dialogue (encourages broad and insightful thinking and discussion about the topic). According to its type, this is a constructive one that goes beyond state-of-the-art analysis to propose new interpretations and to build a case for a specific course of action. First, the paper elaborates on the foundational notions, current trends, and recent developments that trigger the current changes. It critically analyzes recent significant developments, with a focus on the issues related to emerging NG-CPSs and the reasons why these systems can no longer be described by the traditional combination of words (i.e., cyber-physical) correctly. For this reason, the issue of paradigmatic characterization will be revisited in the context of NG-CPSs, and their cognitive-cyber-physical-social-human (CCPSH) nature will be explained.

1.4. Contribution and Content of the Paper

This paper is written in an academic tone appropriate for the journal Innovation in Pedagogy and Technology. It is structured to answer the research questions introduced above. The scientific contribution includes the following: (i) a detailed insight into the dynamic evolution of the paradigm of CPSs and shedding light on the implications on the education for next-generation systems, (ii) a critical analysis of the epistemological and methodological opportunities for PDEE and TDEE, and (iii) an investigation of the best practices to support progression in cursory, autonomous, and lifelong education is the context of CPSs. Attention has been paid to conceptual coherence, epistemic depth, and semantic interlacing of the concepts, while textbook-level discussion and superficial lists have been avoided. The suggestions of the author have been formulated as propositions. The next Section revisits the foundational concepts, definitions, and interpretations related to innovation in engineering education, epistemology of scientific knowledge, and artificial intelligence technologies. Section 3 provides a critical survey of the system paradigm of CPSs. It addresses its foundational assumptions and essence, discusses the manifestation of CPSs, and identifies the strands of the current paradigmatic evolution. The last subsection provides a personal view on next-generation CPSs. In Section 4, the paper closes with some reflections and explains its relation to a follow-up publication.

2. Revisiting Foundational Concepts, Definitions, and Interpretations

The main title of this position paper associates five specific domains of interest, which - without any prioritization - are: (i) innovation in engineering education, (ii) post-disciplinary and transdisciplinary scientific knowledge, (iii) evolving CPSs, (iv) concepts and technologies of artificial intelligence, and (v) pedagogical and andragogical theories and practices. It was surprising to find, at the time of designing a systematic literature study, that the often-mentioned differences in interpretation of concepts indeed existed in each of the domains, as well as confusing terminologies, and ontological and notional dispositions. Consequently, to have a consistent terminology and meaning structure, this section is devoted to explaining my interpretation while trying to unify terminology across the fields concerned. It is hoped that it helps achieve notional agreement and freedom from argumentative contradictions in addressing such a complex topic. It is also hoped that the provided consistency-seeking definitions and the elaboration on the foundational concepts and their relationships will provide consistent information to establish a robust notional and reasoning framework in the following sub-sections. The contents of the sub-sections are arranged in the order given above.

2.1. Notions and Concepts Related to Innovation in Engineering Education

Engineering education is a historical phenomenon that is adapted to the development of knowledge, artifacts, technologies, applications, society, and businesses. I regard the institutionalization of systems engineering as a constituent of foundational epistemology[7] rather than as a disciplinary subfield[8]. SOEE has generally been centered on disciplinary knowledge, functional and architectural archetypes, model-based development, component-level optimization, and lifecycle-oriented knowledge structures. Contemporary literature reflects a shift from discipline, theory, and component-centric instruction to a holistic, formative system-centered education that places systems thinking at its center[9]. The practice of SOEE has been driven by mainstream pedagogical innovations that abandon the conventional, teacher-focused, and structured didactic strategy (which deliberates and designs how, what, and why to teach, plan, control, and deliver by the instructors). Many innovative ideas have been proposed to achieve transformative developments in engineering and systems education. Moving beyond traditional teaching and learning, the latest initiatives seek to introduce creative strategies, programs, technologies, courses, and approaches to enhance engagement, efficiency, and outcomes[10].

Asbjornsen and Hamann correlated systems theory and engineering education and referred to them as targets for education[11]. They assumed that a major task may be to educate the normal engineering educators in systems thinking and systems engineering to succeed with the integrated concept of SOEE. They evaluated four different concepts of education in systems engineering, namely the (i) new discipline concept, (ii) graduate education concept, (iii) industrial education concept, and (iv) integrated engineering concept, against the requirements defined for the education, as seen from the various stakeholders, the students, the university, the industry, and the faculty. They concluded that a concept-integrative approach to engineering education offers the most opportunities and advantages. Along these lines, efforts have been made to develop a top-down knowledge transfer.

Michael, K. et al.[12] investigated the potential of AI-based systems for higher education and stated that harmonization is required to provide the most appropriate solutions according to the needs of students and teachers, as well as university administration. Their major finding is that future goes to shift to an “education on-demand” model, instead of the “education on-service’ model. An “education on-demand” approach is in which (i) a vision about the development and demands is formed, (ii) lecturers create contents in modular chunks, (iii) the selectable modules are stored in the learning management platform of choice, (iv) open access and administrative handling are available at any time, (v) the learner can select and compose modules depending on the intentions, (vi) the study items and assessment items are adjusted to the goals, (vii) the assessment items are graded automatically, (viii) personalized advised is generated concerning follow up, and (ix) adjustments and updates of the contents are done by lecturers.

Recently, curricular content development has shifted from reductionist content delivery to application-integrated delivery and incorporating constructive pedagogical elements to intensify the synthesis and consolidation of knowledge. As an example, designing under uncertainty has become a daily educational routine, squeezing out the old practice of optimizing under stability. These are often referred to as transformative innovations. They complement supportive innovations such as high-fidelity learning environments. Nevertheless, due to shifts in various system paradigms, SOEE is now facing the challenge of fundamentally redefining what counts as "core knowledge" for CPSs and NG-CPSs.

For long, SOEE meant only human-object/content-human relationships. However, the evolution of systems has recently created a situation in which other relationships, such as system-object/content-human, human-object/content-system, or system-object/content-system, should be considered. The entirety of these is shown graphically and annotated in **Figure 1**. Awareness of this abrupt development is important because new concepts that were not associated with the traditional human-object/content-human relationships have already emerged, related to alternative relationships. Both training and intellectualization of systems (i.e., cognitive design and engineering) and teaching and training by systems (i.e., using intellectualized systems as educational agents) have become part of the widened domain of engineering education. These new concepts not only further articulated but also transformed the meaning of SOEE, requiring the refreshment of the related human mental models.

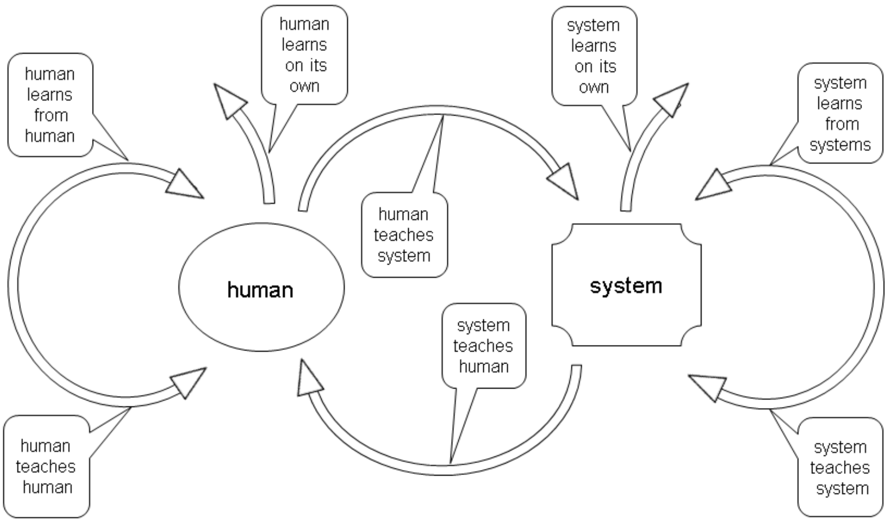

Figure 1. Relationships between humans and engineered systems from the perspective of sharing knowledge and other cognitive competencies.

Many principles have been applied to categorize innovations in SOEE based on their nature. The two basic categories that have been considered widely are (i) transformative innovations and (ii) supportive innovations. While these two categories of pedagogical innovation are typically consistently interpreted in literature, other notions (e.g., innovation concepts) are not always sharply demarcated. Transformative innovation in SOEE includes attitude and competence enhancement by mastering (i) model-based systems engineering, (ii) lifecycle-oriented engineering, (iii) operationalization of prognostic systems thinking, (iv) system design based on digital thread/twin concepts, (v) integration of AI as a daily pedagogical co-agent, (vi) problematization through wicked problems, (vii) increase of social-constructive elements in education, and (viii) familiarization with self-driven learning methodologies[13]. Supportive innovations involve (i) integrated content and process management systems, (ii) online content provisioning and assessment, (iii) physical and online mixed reality labs, (iv) management of personalized/adaptive learning pathways, (v) connectivity for multi-stakeholder negotiation, (vi) use of biometrics in educational contexts, and (vii) advisory service for handling uncertain contents, to mention just least domain specific ones.

The review of contemporary literature has revealed a wide spectrum of innovations affecting the education of CPSs. It indicated that technological innovations have received more attention over the last three decades. However, without corresponding epistemic, methodological, psychological, etc. innovations, there is a danger that technological innovation merely accelerates outdated educational practices and/or is misused to automate outdated pedagogy[14]. If not embedded appropriately, technological innovations may remain fragmented or be reduced to attractive technological novelties. Rather than the other way around, pedagogy in CPSs education must lead technology innovation, not just follow it. This explains why various authors proposed to consolidate CPSs-related engineering education into a framework having three interdependent layers: (i) epistemic, (ii) methodological, and (iii) technological. Notwithstanding the possibility, instead of all purely technology- or didactics-oriented taxonomic models for SOEE, I see both the necessity and the advantages of using a more comprehensive conceptual model. Dubbed the 'six-aspect pedagogical innovation model', the proposal is shown in **Figure 2**. The figure also includes lists of concrete examples of innovation. The order of mention of the various examples is arbitrary, no significance or priorities have been considered.

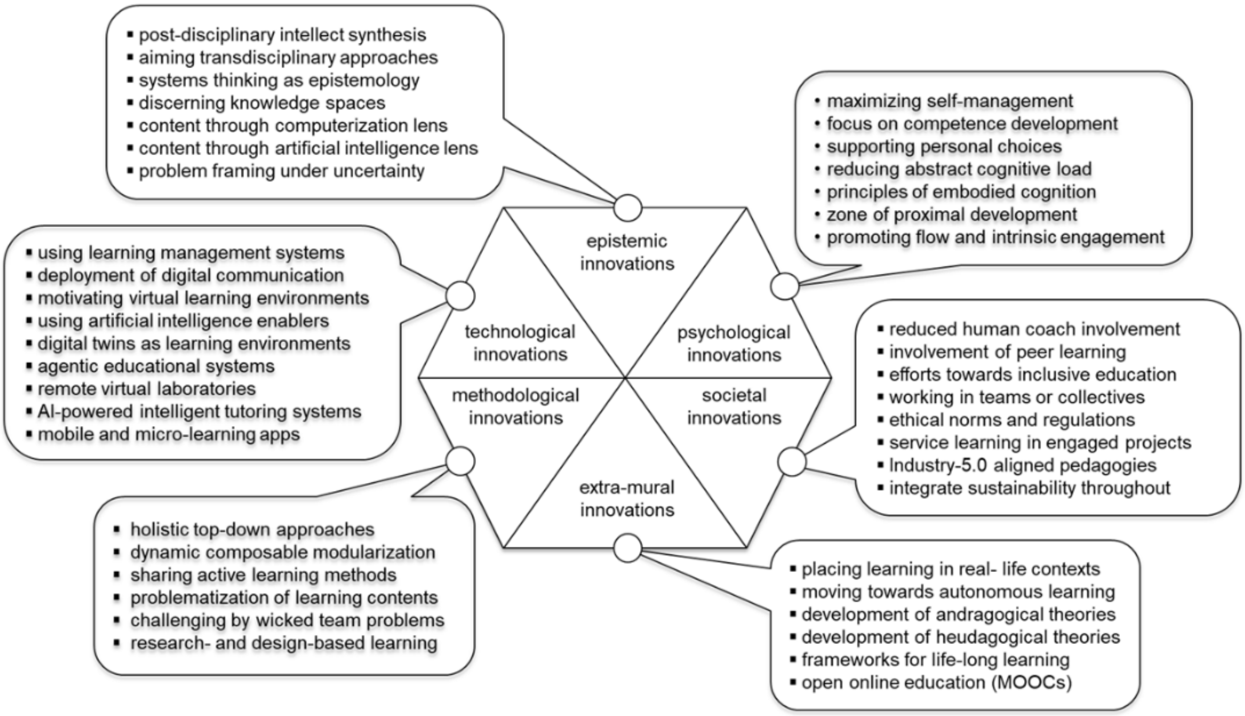

Figure 2. The six-aspect pedagogical innovation model for engineering education and examples of mainstream innovations.

The central claim of epistemological innovation in SOEE is that traditional reductionist and empiricist epistemology insufficiently fosters the required deep conceptual understanding and higher-order thinking skills necessary for epistemic tasks in both scholarly research and systems engineering[15]. Epistemic innovations also concern the organization, integration, synthesis, and operationalization of knowledge driven by the need for post-disciplinary and transdisciplinary bodies of knowledge. The most significant shift is the transition from discipline-centred knowledge structures toward knowledge spaces organized around system paradigms and integrative problems. Systems thinking is no longer treated as a supplementary skill but as a foundational epistemology. Learners must develop epistemic fluency, which is understood as the ability to navigate, integrate, and critically evaluate heterogeneous forms of knowledge, models, and representations across disciplinary boundaries.

Technological innovations in SOEE cover a wide range and provide new infrastructure and tools for learning. Recent major ones are: (i) AI-based tutoring, assessment, and learning analytics, (ii) digital twins as epistemic laboratories rather than demonstration tools, and (iii) agentic systems that support planning, reflection, and adaptive scaffolding. Being heavily biased by the proliferating generative AI[16], present-day technological innovation concentrates on the opportunities offered by AI tools for online platforms (e.g., AI-

MOOCs), immersive (e.g., virtual classrooms/labs), personalized assistants (e.g., AI tutors), and streamed data analytics (e.g., powered by cloud computing). Artificial intelligence enables adaptive tutoring, formative assessment, learning analytics, and personalized feedback. Digital twins serve as epistemic laboratories by which learners can explore system behaviour, test hypotheses, and experiment with design decisions without real-world risks. Agentic systems increasingly support planning, reflection, and adaptive scaffolding of learning processes. The goal is to achieve more dynamic, personalized, and lasting learner experiences and, ultimately, have more capable and curious learners.

Methodological innovations in SOEE concern how knowledge is constructed, transferred, and applied. In the context of NG-CPSs education, system conceptualization under uncertainty rather than model-based solution optimization under stability should be increasingly emphasized. Real-life wicked problems, open-ended design challenges, and scenario-based reasoning need to replace pre-defined closed-form exercises. Often-cited methodological approaches are project-based learning, explorative learning, and challenge/problem-based learning. The main pedagogical elements are self-organized teamwork, innovative synthesis, systems thinking, societal impact, and eventually cooperation across multiple institutions and with industry or community stakeholders. The plurality of models in reasoning and creative work is encouraged, acknowledging that multiple, partially valid frameworks, models, and representations may coexist. Learning activities, therefore, need to focus on synthesis, negotiation, and reflective judgment rather than procedural correctness alone. This is a hot topic in the context of NG-CPS due to the lack of demonstrable full-scale prototypes, as appears in the literature.

Extra-mural innovations extend the real (institutional) space of SOEE with alternative spaces facilitated by digital computing, knowledge repositories, network access, and AI technologies. They create a bridge between pedagogy and andragogy. In its literal meaning, pedagogy deals with personality and competence development of young individuals, while andragogy focuses on continuing learning of adults. Both domains of SOEE have been covered by many learning theories and methodological frameworks at all levels of organized institutionalized education, particularly in the context of higher engineering education. The considered contemporary learning theories can be sorted into five groups: (i) active/constructivist, (ii) challenge/problem-based, (iii) competency/outcome-oriented, (iv) socially sensitive/human-centred, and (v) AI-aware/agency-focused learning theories. Nevertheless, in the case of NG-CPSs, further dedicated extra-mural innovations are necessary from both andragogical and heutagogical perspectives.

According to many experts, SOEE has been quietly reinventing itself over the last couple of decades by addressing not only epistemological and technological issues, but also how we teach, who gets access, and what engineers are expected to care about. This trend is often referred to as socialization. Societal innovations mirror how engineering works and how engineering solves complex problems in a society-respecting manner in the real world. They (i) pursue a balance between extensive hard skills and complementary societal soft skills, (ii) increasingly target technical, professional, and meta-skill competency profiles, and (iii) align curricula, assessments, and micro-credentials to them. Various competency-based and outcome-oriented methodological frameworks have been proposed to facilitate active learning and the construction of knowledge by teams or collectives of students through doing, feedback, and reflection. Based on these, there has been a dominant shift from passive, teacher-centred instruction to active constructivist learning by collective participation as the baseline[17]. Another aspect of socialization is open education and offering free educational resources in the form of open courseware (e.g., YouTube lectures, MOOCs, GitHub, open textbooks). Gatekeeping is slowly but visibly shrinking. Regarding SOEE, it means that elite-level knowledge is no longer locked in elite universities.

Psychological innovations have no universal goals or approach in engineering education. They are necessitated by the shift in focus from purely technical training to developing human-centric, adaptable, and emotionally intelligent engineers. Key approaches include fostering student autonomy, integrating empathy into design, utilizing active, emotion-driven learning, and adopting human-centred engineering models to tackle complex societal challenges[18]. It seems that they are guided by the different principles of the seven widely accepted philosophies: (i) essentialism, (ii) progressivism, (iii) perennialism, (iv) existentialism, (v) behaviourism, (vi) linguistic philosophy, and (vii) constructivism. Each philosophy provides a different perspective on what and why to teach, how to teach, and what psychological effects to consider. Psychological innovations are multi-faceted, including (i) using psychological (cognitive and behavioural) principles and approaches to optimize learning, (ii) emphasizing human-centred engineering and empathy, (iii) preferring satisfaction-oriented education, (iv) operationalization of emotion-driven design, (v) building professional identity and attitude, (vi) incorporating emotional intelligence is self-learning processes, (vii) promoting the engineering, professionalism, innovation, creativity (EPIC) framework, (viii) investigating the influential factors of autonomy and self-regulated learning, and (ix) nurturing critical thinking and socio-emotional competencies in engineering courses.

2.2. Notions and Concepts Related to the Epistemology of Scientific Knowledge

Convergence and divergence are notable trends in science that complement each other. Convergence triggers the formation of supra-disciplinary scientific knowledge, including composite forms of understanding, theories, methodologies, and conceptual frameworks that transcend individual scientific disciplines and enable integration, coordination, and synthesis across them. On the other hand, the fusion of the above lends itself to the emergence of new research questions, methodological approaches, and eventually novel interest domains. The convergence and divergence processes have largely contributed to the development of the system paradigm of CPSs. They stimulated new research interests but also raised challenges for the education of CPSs. In my view, CPSs (i) fundamentally destabilize the classical disciplinary structure of science, (ii) necessitate supra-disciplinary approaches in research, (iii) need shopfloor coadunation (merging and uniting into a single body) of expert teams in system development, and (iv) raise the need for innovations in engineering education.

On the way towards genuinely supra-disciplinary knowledge and practices, the current challenges are catalysts for forming mindsets to undertake the necessary scholarly activities and facilitating a shared understanding of post-disciplinary and transdisciplinary scientific knowledge. Many researchers have observed that the latter is indispensable due to inconsistent use of vocabulary and misinterpretation of the various modes of scientific conduct. **Table 2** has been included below to show the interpretations used in this paper. It is worth mentioning that the term ‘interdisciplinary’ is often used as a ‘jolly-joker’ (a wildcard) to indicate various combined disciplinary contexts. Pluri-disciplinary scientific knowledge refers to the production and use of knowledge that draws on multiple scientific disciplines while preserving their distinct theoretical frameworks, methods, and epistemologies. Knowledge is additive rather than synthetic. Each discipline contributes in parallel, retaining its own concepts, methods, standards of validation, and explanatory models.

Table 2. Four-tier comparison of disciplinary modes.

Mode	Ontological Aspect	Epistemological Aspect	Methodological Aspect	Praxiological Aspect
Mono-disciplinarity	Accepts a single domain of reality defined by one discipline	Knowledge is discipline-specific and internally validated	Uses established methods of one discipline	Solutions and applications stay within one domain
Multi-disciplinarity	Multiple realities exist, but remain separate	Knowledge co-exists but is not integrated	Parallel use of different disciplines’ methods	Combined results, but discipline boundaries remain
Inter-disciplinarity	Assumes overlapping or shared aspects of reality	Integrating knowledge to solve a shared problem	Methods are blended or borrowed across fields	Joint solutions, but still discipline-aware
Cross-disciplinarity	One domain intentionally looks at another	Knowledge borrowed across fields, but still hierarchical	Methods of one field are applied to another	Often instrumental: One discipline serves another
Post-disciplinarity	Rejects fixed disciplinary boundaries altogether	Knowledge is situational and fluid	Methodological bricolage: Whatever works	Context-driven, focus on problematics, often pragmatic or instrumental
Trans-disciplinarity	Reality is complex and beyond any single discipline	Knowledge transcends disciplines and includes non-academic sources	Mixed and emergent collaborative methods	Oriented toward real-world complex problematics also important for stakeholders

Table 2. *Cont.*

Mode	Ontological Aspect	Epistemological Aspect	Methodological Aspect	Praxiological Aspect
Supra-disciplinarity	Envisions a higher systemic reality above disciplines	Seeks ultimate meta-knowledge or holistic universality	Highly synthetic or axiomatic methods (e.g., systems theory)	Grand unified approaches, often theoretical or ideological

CPSs are instantiated at the intersections of physics, computer science, biology, cognitive science, social sciences, and design disciplines. As such, CPS knowledge is better described as post-disciplinary rather than interdisciplinary. The evidence for this is: (i) hybridization of material, energy, informational, computational, biological, and social processes, (ii) recognition of co-production of knowledge between experts, stakeholders, and affected communities, and (iii) proliferating use of transdisciplinary design and development practices, where problems are framed jointly by academic and non-academic actors (industry, policy, civil society). Additional core characteristics of this knowledge domain include: (iv) integration into supra-disciplinary research frameworks, (v) using problematics implied research models and designs, (vi) relying on complexity science, crowd science, and emergence theory[19]. In this sense, higher education of CPSs and NG-CPSs requires the development of epistemic fluency, i.e., the capacity to navigate, integrate, and critically reflect upon heterogeneous forms of knowledge and transdisciplinary or (even) supra-disciplinary approaches. A bottom-line educational implication is that foundational CPS knowledge should not be presented as discipline-specific content but as a means, or the ability, to generate coherence across previously distinct epistemic domains.

Liu and Tran provided a historical overview of the discussions and scholarly works on transdisciplinarity and identified features of a transdisciplinary orientation[20]. They argued that the transdisciplinary activities in the practice of engineering and SOEE do not appear substantially different from interdisciplinary activities, except that they may more likely engage non-academic stakeholders and position themselves as innovative. While there appear to be plenty of opportunities for engineering educators, researchers, and engineering schools to engage with transdisciplinarity, a fundamental conceptual change is needed to enable a real transformation. The review of the above authors revealed that the gaps between conceptual discussions and practical representations suggest a long way to go before truly transdisciplinary visions can be fulfilled in engineering education practice. Evolution of systems engineering under the influence of artificial intelligence has also caused terminological and conceptual issues (for instance, what is meant by the phrase “intelligent system”?). This, and similar concerns, will be addressed in the next sub-section.

2.3. Notions and Concepts Related to Artificial Intelligence Technologies

Many researchers agree that one of the largest influences on engineering education has been made by computerization, which has been a continuing and strengthening process. Lyngdorf et al. inventoried and compared various pedagogical, technological, and entangled frameworks of digitalization[21]. They proposed a reasoning model that correlates the observable pedagogical outcomes of digital technologies with three educational levels. At the micro-level (individual competence building), the mentioned forms help: (i) attitude, knowledge, and skills development, (ii) affective development, (iii) cognitive development, and (iv) behavioral change. At mezzo-level (across departments and universities), they can promote (i) connectiveness of institutional contexts, (ii) interdisciplinary collaboration, and (iii) personalized learning environment development. At the macro-level (larger global and societal perspectives), they foster (i) data accessibility, (ii) environmental innovation, (iii) international connections, (iv) operational cost savings, and (v) lifelong learning.

In my interpretation, based on their change potentials and concrete objectives, various stages (epochs of development) can be identified in the persistent process of computerization, in line with technological developments. These epochs are shown in **Figure 3** as transformation stages. The advent of the various epochs of digitalization (informatization, smartification, intellectualization, and intelligentization) has left footprints on engineering education, offering numerous benefits and advancements. Considering this model, I see the current all-embracing phenomenon of artificial intelligence as a stage in the progression of deploying digital computing in our daily educational reality. In the absence of cloud-based computing, massive data processing/storage, and cognitive science research, the emergence of large language models and the concept of agentic actors would not be possible.

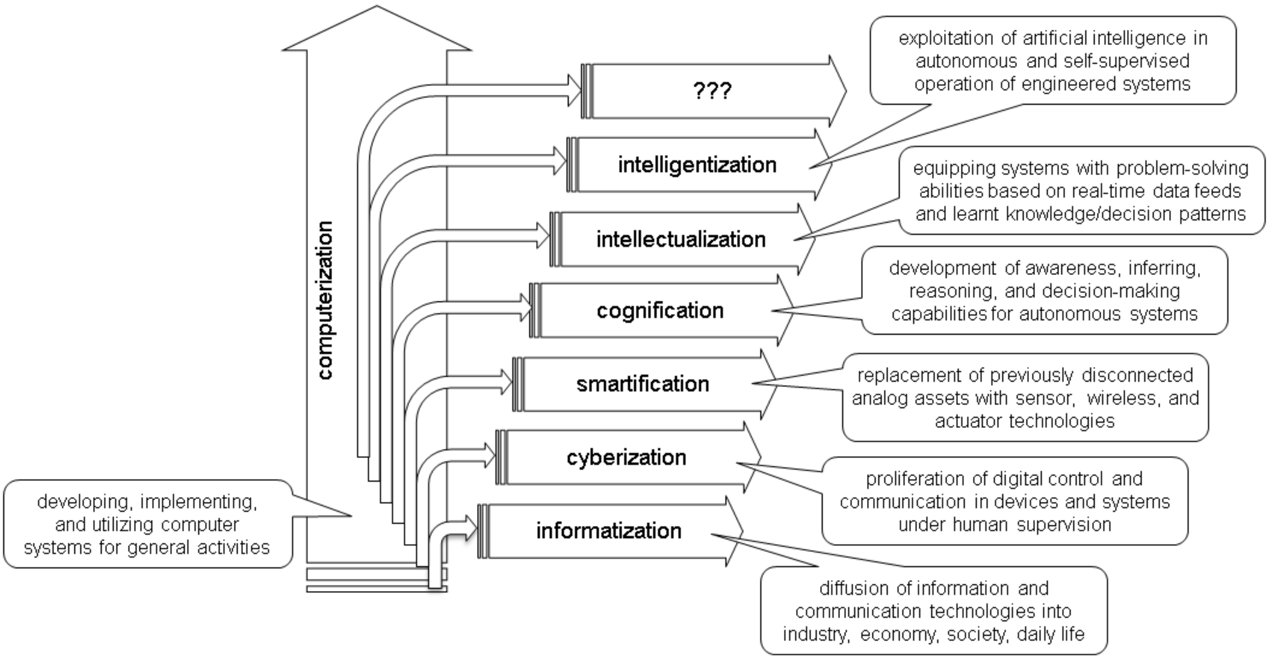

Figure 3. Epochs of the deployment of digital computing.

On the one hand, rapidly evolving artificial intelligence technologies have had a large influence on the manifestations of engineered systems, involving CPSs. The aggregation of these influences has led to a remarkable change in the paradigm of this family of systems. Often in an exaggerated manner and without clear technical objectives, the phrase 'artificial intelligence' is one of the most frequently used technical expressions nowadays in the context of CPSs. No wonder that it has created many buzzwords and definitional uncertainties, as well as vagueness and indeterminism, even in specific scientific papers. There are deep notional, philosophical, and scientific issues behind it that boil down to the probability and possibility of artificial systems intelligence. Most sources correlate system intelligence with human intelligence, disregarding important teleological matters. As discussed by Keller[22], if we intend to compare human intelligence with any other natural and/or artificial forms of intelligence, we need a universal definition of what intelligence is. However, as is well-known, we do not have such a definition. This explains the very different conclusions about the intelligence of engineered systems that various authors have proposed. Many definitions claim that system intelligence is essentially the capability of solving problems, complemented by the ability to learn from experience and to adapt to and/or shape the environment. Teleologically, systems intelligence is acquired (learned, reasoned, and constructed), rather than evolved (human-like) intelligence.

Obviously, the above conceptualization reflects a reductionist view that forgets about the direct relationships between experienced cognitive behaviour and the physicality of the concerned system-and-environment duals. A holistic view would consider higher-order intellectual and sentient abilities (e.g., abstraction, intuition, imagination, emotions, etc.). On the other hand, the definition mentioned above associates system intelligence with executive functions, which consist of abilities such as inhibitory control (i.e., preventing impulsive or premature actions), working memory (the ability to hold information in mind and manipulate it mentally), and cognitive flexibility (the ability to change the approach to a given problem, if the circumstances require it). Research in problem-solving-oriented intellectualization of engineered systems has recognized the need for a deeper understanding of the relationship between intelligent behaviour and the functions and relationships of the human brain and body[23]. This has influenced the development of neural network models and architectures and has led to their extension with semantics-handling structures.

To create a robust platform for the following discussion of AI in current and NG-CPSs and their various roles in SOEE, a concise overview of the major technologies is presented below. Reflecting my perspective and understanding, **Figure 4** shows a possible classification of AI technologies by their computational nature. The clockwise positioning indicates the order of their emergence in time, neglecting factual overlaps. Considering the used representation of knowledge, the approaches shown can be classified into four ontological categories: (i) symbolic (symbolist, analogist, probabilistic), (ii) sub-symbolic (evolutionist and connectionist), (iii) meta-symbolic (generative and agentic), and (iv) post-symbolic (embodied and bio-inspired). A shared feature of this last category, and probably of the emerging ones, is that they are related to physical substance. In my view, the 'traditional' symbolist and sub-symbolic technological approaches are not second to the currently widely studied meta-symbolic and post-symbolic approaches (the emerging corporeal approaches) in their importance. In relevant applications within current and NG-CPSs, they may outperform the newcomers by using less data and computational resources. Occam's razor works in this context, too. This is an important aspect to radiate in CPS education and provide convincing practical examples.

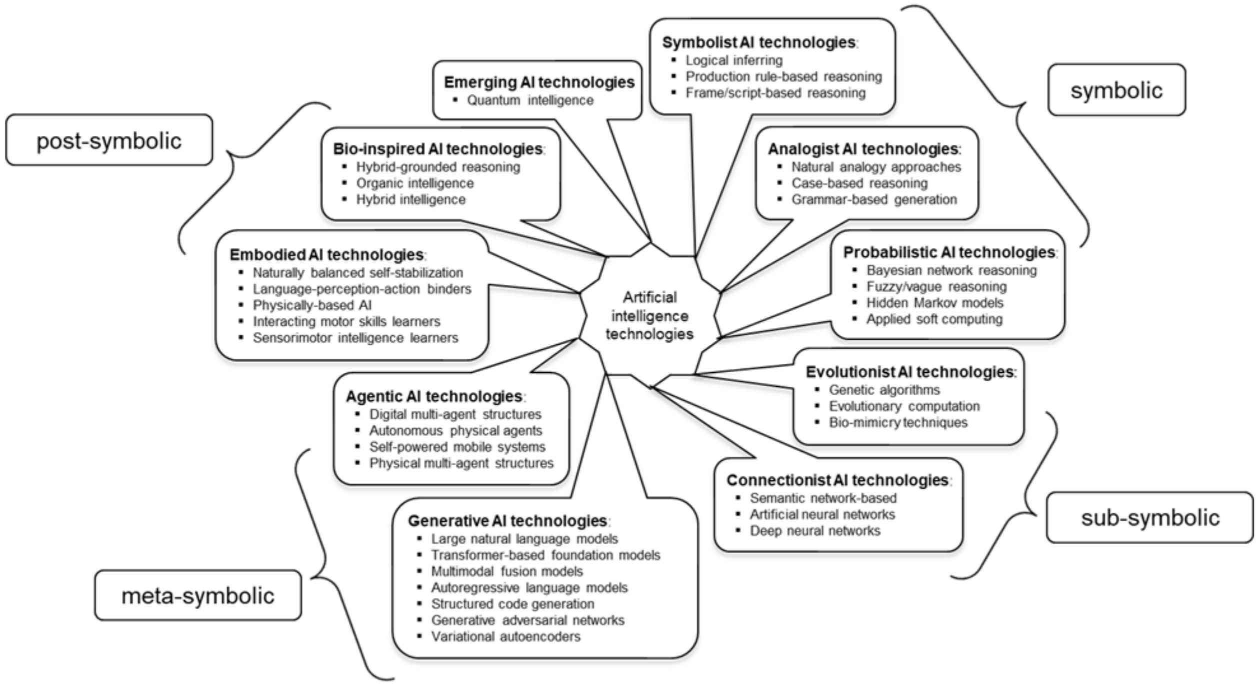

Figure 4. Classification and overview of AI technologies.

Artificial intelligence (AI) research and development has produced a wide range of technologies developed over the past sixty years to replicate aspects of human intelligence through cognitive computational models or endowing systems with cognitive capabilities. Since its emergence, AI research and development have strongly influenced systems research, education, and engineering practice, steering technological progress toward specific capabilities and application domains. By now, two ontological categories of reproduced intelligence have been developed: (i) computational intelligence (or disembodied intelligence that exists only in digital form), and (ii) corporeal intelligence (or embodied intelligence that exists in the material realm and has a real or simulated carrier body)[24]. The various approaches are also often referred to as digitally based (disembodied) and physically based (embodied) AI[25]. The basis of differentiation is that digitally based AI learns only from data and reasons with patterns, while physically based AI learns by acting in the world and reasons in environmental contexts. The fact of the matter is that neither one of the two categories is pure. In particular, the physically based category of technologies involves digitally based constituents (such as physical multi-agent structures).

The latest technologies have significantly enriched the vocabulary with new technical words and jargon. They have also introduced the pedagogical concern of proper understanding of the essence and differences of these technologies, behind the widely varying journalistic denominations. First, from the perspective of CPSs, understanding the representational, computational, and deployment differences between the two main ontological paradigms is essential. The basis of disembodied (a.k.a. digital, computational) AI is symbolic inference and statistical computation. It operates only with abstract representations and manipulates logic, data, and language[26]. Embodied (a.k.a. physical, substance-related) is grounded in the perception → action → feedback loops. It resides on four assumptions: (i) having a body that physically interacts with the surrounding world, (ii) learning knowledge through multi-modal perception, (iii) developing plans of action, and (iv) providing multi-modal feedback. These assumptions make this category of AI indispensable for NG-CPSs and should be at the centre of education. It enables many more functionalities that can be supported by versatile text-, voice-, image-, and video-oriented generative AI technologies, which have been conceptualized to generate models that create new content based on transformers needing expensive training.

Though often used as synonyms, physical and physically based intelligence mean two different things. Physical intelligence implements cognition in real-world environments by considering possible states of materials, changes of bodily morphology (shape and structure), contextualized sensing, adaptive control, and operational autonomy[27]. On the other hand, physically based intelligence is a transformative approach that uses physical laws, physics simulations, and physical interaction as the primary mechanism for learning, reasoning, and decision-making. That is, it integrates learning and reasoning into cognitive processes of systems based on physical domain-knowledge, where force, motion, energy, materials, and dynamics matter as much as computation. In addition to data and labels, it operationalizes physical laws, conservation principles, explicit causalities, bodily constraints, physical equations, and signal flows to respect the underlying physics concerning the problems of interest in learning and problem-solving processes. Typically, these chunks of knowledge are activated during training and become elements of the architecture of the learnt model. The main advantage of this approach is higher fidelity in capturing physical reality and improved problem-solving. This technology can not only manipulate a physical body but also mimic awareness of physics and causality and create descriptive and explanatory knowledge in various forms (i.e., it connects meaning to action, and vice versa). Some researchers regard it as a complementary strength of this technology.

When used in CPSs and NG-CPSs, mainstream embodied intelligence assumes morphological computation, i.e., processing the environment, system, state, and process information sensed by (bodily) sensors in real time and in a synthesized manner. The main assumption is that the physical components of the system are designed so that their physical bodies, the functional interactions among the bodies, and the changes in the materials perform part of the computation or control normally completed by software. In other words, instead of solving everything with algorithms, the morphology (shape, compliance, materials, geometry) of NG-CPSs does some of the work. However, from the perspective of AI technology, contemporary literature is still lacking underpinning theories and systematic guidance for morphological computation. Neither complete theoretical frameworks nor procedural models have yet been established for morphological computation. Several approaches are known, some of them, like passive dynamic mechanics, material intelligence-enabled soft robotics, and morphology embodied control, represent relatively mature but largely explored categories. Other approaches, such as (i) reservoir computing[28], (ii) information-theoretical self-organization[29], (iii) mechanical signal filtering[30], (iv) mechanobiological timely responses[31], and (v) synthetic mechano-transduction[32], are still in a premature stage. Agentic physical AI targets systems with physically embodied autonomous agency and focuses on the abilities of selecting, planning, and executing actions to achieve goals in the real world. **Figure 5** summarizes the affordances that AI-enabled agents can offer in human-system and system-system interoperation.

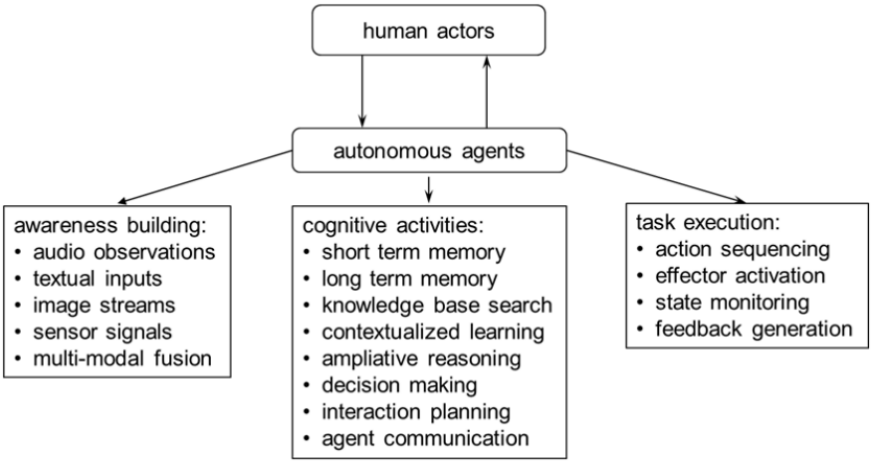

Figure 5. Affordances offered by agentic AI.

Though it sounds evident for many researchers, it must be reassured that even embodied artificial intelligence cannot be anything else but a strongly limited subset of the inherent embodied intelligence of living creatures. Currently, it represents a cutting-edge paradigm, rather than a consolidated technology and CPS development methodology. Education should present it as such, even if there is an emerging but overambitious trend to move towards organic artificial intelligence, which attempts to combine biological, neural, embodied, generative, and post-generative AI approaches into a single technology. Organic and biological intelligence concepts run parallel and inspire many post-generative AI approaches towards integrating autonomy, multimodality, and physical grounding. Consequently, CPS education must address the emerging forms of AI beyond technological literacy, considering them as forms of algorithmic agency, socio-political actors, and co-evolving cognitive partners of humans. Learners must cultivate AI literacy at the same level as systems literacy, understanding not only how AI works, but how it can reshape intellect, behaviour, agency, responsibility, and utility in the case of NG-CPSs.

3. Evolution of the System Paradigm of Cyber-Physical Systems

3.1. Foundational Assumptions and Essence of the System Paradigm

Over the years, many definitions of CPSs have been proposed. An overview of the most frequently cited formal definitions is shown in **Figure 6**. They approached this family of systems from different perspectives and identified different characteristics as foundational. The essence of the traditional CPS paradigm is constituted by several interdependent principles: (i) tight integration of cyber and physical realms, where computation is not external control but an internal, constitutive property of material processes, (ii) continuous feedback loops that dissolve the classical separation between design time and run time, (iii) real-time coupling with environments, making context-awareness a structural property rather than a feature, and (iv) distributed agency, where decision-making is shared across sensors, algorithms, human actors, and infrastructures. Several functional and architectural models have also been published[33].

Scientists attempted to capture the paradigm of CPSs in implementation-independent ‘functional layer-models’ in which each layer utilizes different resources and knowledge and contributes specific generic functions. The three-C, five-C, and seven-C models, shown in **Figure 7**, have become popular for explaining the ontology of CPSs, though other interpretations have also been published. The lower layers are closely related to computation[34]. In the context of such stratified models, learners must understand that a layer is not an ontological partition of reality, but a mental decomposition for reasoning and intervention. My view is that all textual specifications are necessarily incomplete and static in time, and layered models are unnecessarily abstract.

Together with the ontological status of CPSs, technological fundamentals and enablers in and beyond industries, and application opportunities in a European perspective, the definitional issue has already been addressed in an early position paper by Horváth and Gerritsen[35]. Like some other forerunning and many subsequent publications, this work argued that a more robust notional dispositioning was needed. The reasons are as follows. First, CPSs are not merely technological artifacts, but complex epistemic constructs emerging from the convergence of engineering technologies, scientific knowledge, artificial intelligence, and contemporary learning sciences in a post-disciplinary manner. Second, traditional engineered systems represented human intentions through static structures, whereas CPSs enact intentions through continuous sensing, computation, actuation, and learning. Third, CPSs represent a fundamental epistemic and functional shift from traditional mono-disciplinary or cross-disciplinary engineered systems toward hybrid ontologies. These are the exact reasons why the system paradigm of CPSs is sensitive not only to scientific and technological trends, but also to societal and ecological developments. Functionally, the CPS paradigm is a distinct and coherent set of intrinsic concepts and patterns of features that determine what constitutes legitimate belonging to a particular category of engineered systems. It renders the shift from representational systems to performative systems. Evidently, this also influences the educational dimensions of CPSs.

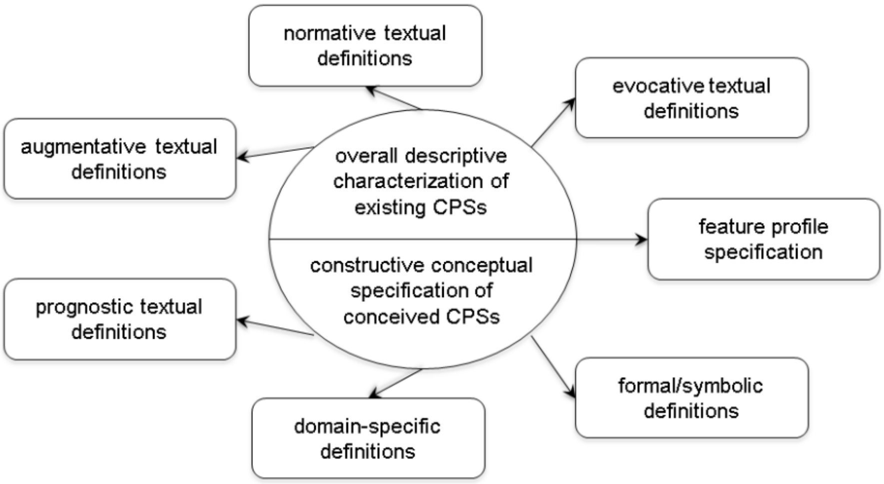

Figure 6. Types of definitions of cyber-physical systems.

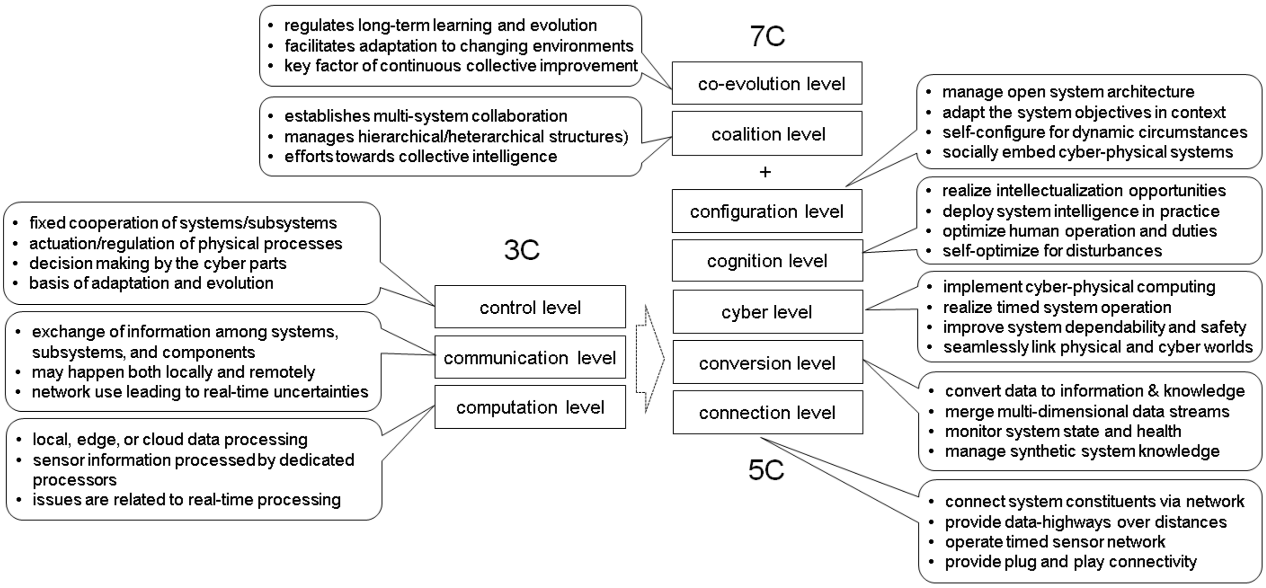

Figure 7. Functional layers of CPSs according to the three-C, five-C, and seven-C models.

As interpreted in this paper, an archetype of CPSs relies on four foundational functional assumptions and three foundational conceptualizations. These together define its system paradigm. The first assumption is agency. It means that these systems have actors (agents) that dynamically interact with each other and their environment to achieve goals. The second assumption is autonomy. These systems have the capacity for self-governance and the ability to make independent choices (decisions) regarding their behavioural objectives. The third assumption is penetration. It expresses the deep real-time diffusion of these systems into real-life natural and/or created physical processes through concurrent actions. The fourth assumption is evolution. It is the ability to combine problem-solving and state monitoring with holistic learning to change the inherent characteristics of these systems and adapt continuously. The three foundational conceptualizations are: (i) reflecting integrative systems thinking, (ii) deploying computation as a structural property, and (iii) creating tight coupling between physicality and cybernetics. The above assumptions and conceptualizations are unique in the sense that they have strong distinguishing power. What it means is that (i) CPSs can be distinguished from other engineered systems paradigms (e.g., socio-technical systems, Internet of Things systems, or advanced mechatronics systems), and current CPSs and NG- CPSs can be described equally well based on concrete sets of paradigmatic features.

CPSs educators need to understand the implications of generative AI technologies and study how to adapt to the engineering education ecosystem to ensure that the next generation of engineers can benefit from these advancements while minimizing any negative consequences. Qadir highlighted the importance of recognizing the limitations of generative AI systems such as ChatGPT, CoPilot, and others[36]. Although the foundational technologies are impressive, they can retrieve and compose from what has been published and is accessible on the Internet, but do not possess human-like intuition, critique, and semantic understanding needed for true conceptual innovation. The outcome sometimes is flawed because they rely on training data that can perpetuate biases or spread misinformation. Literature widely discusses that using generative AI in education raises various ethical concerns, including potential misuse by students and the risk of replacing human jobs. Ultimately, the current state of these tools is only a glimpse of what lies ahead. From a pedagogical standpoint, effective use depends on answering key questions: When can GenAI serve as a virtual, intelligent, and personalized tutor? What are the different ways GenAI systems can be utilized? What are acceptable and unacceptable methods of using GenAI? And how do prior experiences, existing knowledge, and professional backgrounds influence their application?

3.2. Manifestations of Cyber-Physical Systems

CPSs are objects of perpetual diversification. It happens in three realms, namely, in the (i) epistemological realm (disciplinary diversification), (ii) cognitive realm (intellectual diversification), and (iii) deployment realm (application diversification). The known forms of manifestations in the above realms are shown in **Figure 8**. Due to space limitations, this figure is incomplete in the application and the epistemological realms. For instance, in terms of application diversification, it could be extended with planetary, infrastructural, societal, companion, sub-micro, etc. applications. Nevertheless, the message of this figure is that CPSs should not be interpreted merely as technological implementations of systems for application domains. Each manifestation foregrounds a wide range of functional capabilities, implementation features, system properties, and human relationships. From an educational perspective, each manifestation reflects distinct modes of coupling between physical processes, computational intelligence, human agency, and socio-ecological context[37]. The diversity of CPS manifestations and the variety of the characteristics should be made transparent in introductory courses. The fact that each manifestation foregrounds different epistemic demands implies that education for CPSs requires epistemic flexibility, in addition to effective educational approaches. In other words, it cannot be standardized around a single curricular archetype that relies on a dominant locus of agency, scale of operation, and degree of socio-technical embedding.

CPSs should not be interpreted merely as technological artifacts or application-specific solutions. From both epistemological and educational perspectives, CPSs manifest as distinct modes of coupling between physical processes, computational intelligence, human agency, and socio-ecological context. Manifestations differ in scale, knowledge integration, functional spectrum, forms of systems thinking, degree of distribution, locus of control, level of autonomy, normative embedding, paradigmatic features, etc. For instance, industrial and infrastructural CPSs represent tightly coupled cyber-physical configurations optimized for reliability, performance, safety, and lifecycle efficiency. Societal CPSs operate at the interface of technology, multi-stakeholder governance, ethical accountability, socio-political impact, and public life. Personal and assistive CPSs focus on close human-system affective interaction, trust calibration, and individualized adaptation. Ecological CPSs operate across large spatial and temporal scales, under deep uncertainty, and environmental interdependence. Consequently, though they foreground specific educational demands, understanding the differences in CPS manifestations is essential for education.

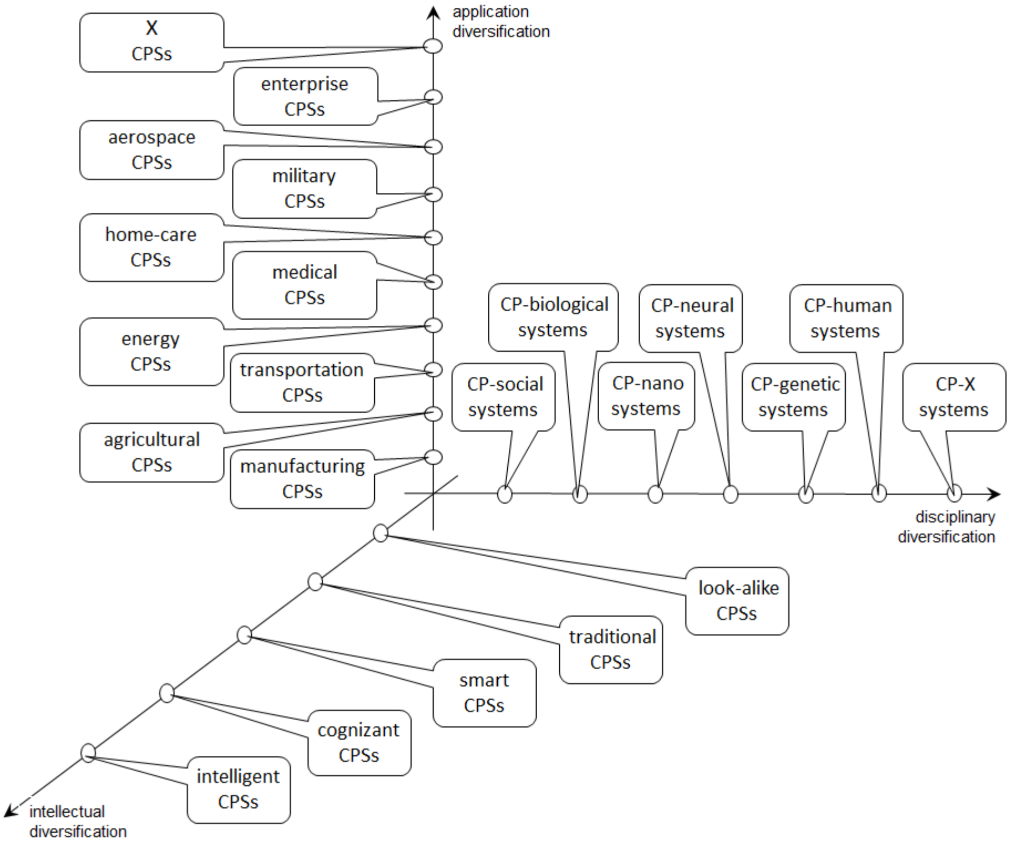

Figure 8. Realms of evolutionary diversification of CPSs.

3.3. Strands of Paradigmatic Evolution of Cyber-Physical Systems

A lot has changed in systems engineering over the last fifteen years due to large-scale trends, such as scientific convergence and divergence, technology integration and knowledge synthesis, the growth of cognitive abilities in engineered systems, the ontological approach of the archetypes of engineered systems, and the compulsion of natural embedding as ecosystems. These trends have had far-reaching impacts on both the paradigm and the manifestations of CPSs. On the one hand, the fact that currently existing CPSs already remarkably differ from those that existed at the end of the first decade of this century caused ontological uncertainties. On the other hand, the prevailing and intensifying epistemological shift to post-disciplinarity has caused disciplinary challenges. In practice, the interplay of these means that the traditional cross-disciplinary (software-dominated and model-, control-, and data-integrated) nature of these systems is being replaced by a discipline-synthetic character, and even towards a transdisciplinary nature in which academic-civil cooperation also plays a key role. It may be claimed that current CPSs have outgrown their original epistemology.

Figure 9 provides a bird's-eye view of the major strands of paradigmatic evolution of CPSs. These strands are (i) disciplinary complexification, (ii) functional intellectualization, (iii) normative socialization, (iv) behavioural personalization, and (v) eco-systemic naturalization. Because of the effects of the trends discussed earlier, they happened sequentially and disconnected at the beginning, but they have become synergistically intertwined by now. Historically, the influence of cognitive science and artificial intelligence research caused the first evolutionary effect. It has created new breakout points for both paradigmatic development and practical implementation of CPSs. The offered cognitive resources facilitated the move towards systems with higher-level operational and problem-solving intellect (reasoning, learning, and decision-making abilities). The enabling processes have been alternatively dubbed as smartification, intellectualization, and, recently, intelligentization. Intellectualization was oriented towards different goals (e.g., reduced dependence on human supervision, autonomous action planning, functional and organizational adaptability, and increased behavioural intelligence level). Built on the concept of system generations, Horváth, I. et al. (2017)[38] proposed a model identifying the milestones of intellectual diversification over time. This model correctly describes the inferable milestones of paradigmatic evolution and serves as a highest-level roadmap. The second-generation CPSs implemented so far share common cognitive mechanisms in solving application problems (e.g., big-data analysis-based reasoning, computational learning, or deep neural learning).

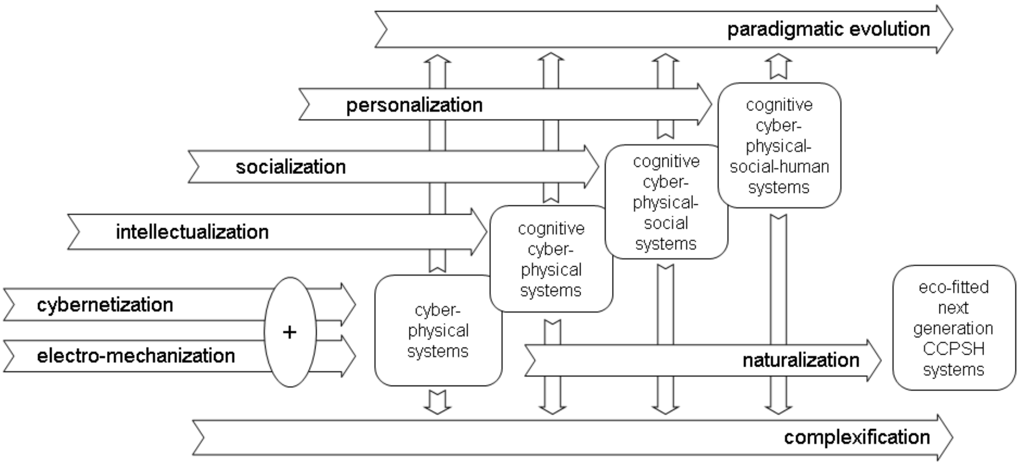

Figure 9. A conceptual model of the strands of paradigmatic evolution of CPSs.

In addition to enhancing cognitive abilities, intellectualization has also stimulated research efforts and paved the way to socialization and personalization of CPSs[39]. These abilities have changed the behavioural and interactional characteristics of systems with humans and other systems. Furthermore, the strengthening of ecological norms and the latest expectations of sustainability regulations necessitate a multifaceted embedding of CPSs in their operational environment as ecosystems. This has stimulated researchers and developers to study the opportunities of their naturalization. It seems that the concept of socializing intellectualized systems should be extended to ecological citizenship, which encompasses social, ethical, and ecological obligations to environmental justice and interests of future generations, in addition to legal and political norms of sustainability and participatory governance[40]. While they all have their own theoretical foundations, development methodologies, and operational requirements, they are also demanded to appear in synergy in cognitive-cyber-physical-social-human systems (CCPSHSs) designs, or simply NG-CPSs.

3.4. Conceiving Next-Generation Cyber-Physical Systems

Historically, three milestones can be identified in the development of CPS systems, namely, establishment of: (i) first generation mechano-electronic systems (with centralized and closed-loop control, and deterministic operation, (ii) second generation embedded and networked systems (distributed computation, networked sensing, and real-time data exchange), and (iii) third generation cognitive, adaptive, and self-evolving systems (with reconceptualization of system constituents as quasi-autonomous agents). Nevertheless, it is always risky to make statements about the future. In the context of NG-CPSs, the discussed fast and intricate development of the system paradigm renders it a challenge [41]. It can already be seen that the lasting changes will most probably influence the ontological status of CPSs. In simple words, it means that NG-CPSs will be fundamentally different systems from the first two generations of CPSs, largely obeying the original paradigm.

Some evidences are: The striving for implementation of human-like intelligence (or at least robust and flexible problem solving intellect or smartness) in CPSs has already created a new situation in which perception, reasoning, and action are not separated into discrete intellectual stages and become a more synergetic constituent of the physical, and not only the cybernetic part, of CPSs The early symbolic artificial intelligence technologies have been substituted by (sub-symbolic) neural technologies in the last five decades. They improved both the learning and the reasoning capabilities. The currently dominant large language models and emerging technologies, such as agentic, embodied, and organic intelligence, are even further broadening the landscape of cognitively enabling technologies of CPSs.

While the current CPSs dominantly exploit digital intelligence, NG-CPSs will most probably benefit from embodied artificial intelligence (EAI). It assumes that their cognitive capabilities will emerge from the continuous interplay among the physical constituents (the body) of the CPSs, the enclosing environment, and the internal information-processing mechanisms of agents and their configurations. Recently, the inseparability of (or the unity between) perception and action has been recognized as a necessary basis of embodied intelligence. On the one hand, EAI creates new opportunities to develop new functionalities and more skilled systems. On the other hand, it (i) extends the scope of the epistemological, conceptual, and computational challenges, (ii) makes the traditional computational models of CPSs obsolete, and (iii) adds further design and operation complexities.

By taking all dominant technological trends into account, it can be posited that the NG-CPSs will (i) leave behind pre-defined models of contemporary CPSs (determinism) and move towards situated self-learning-based, run-time developed probabilistic operational models and adaptive architectures (evolution), (ii) feature application-specific implementation of embodied intelligence together with digital intelligence, and biology-implied AI technologies, (iii) shift from centralized control to fully distributed intelligence and decentralized coordination, (iv) progress from tool-hood type of collaboration to autonomous problem-solving and prognostic partnership, (v) show a metamorphoses from essentially closed techno-social systems to open platform-based ecosystems, integrated with cloud infrastructures, human communities, and socially and ethically regulatory frameworks.

Approaching the same issue from the side of intellectualization, it has already been disclosed that the realization of certain functionalities is extremely complicated or even impossible with purely digital, traditional AI alone (even if deep learning, large language models, or collaborative software agents are considered). A limited set of examples can be the following: (i) real-time biomechanical co-regulation, (ii) adaptive proprioceptive scaffolding, (iii) reflex-level closed-loop intervention, (iv) distributed physical intelligence across body segments, and (v) emergent motor reorganization. NG-CPSs relying merely on sub-symbolic or meta-symbolic representations and reasoning mechanisms cannot physically absorb phenomena, such as architectural instability and morphological changes of state, or exploit passive dynamics. Such affordances will be contributed by embedded artificial intelligence, more specifically, by morphological computation concerning the shape, materials, and physics of the tangible constituents of NG-CPSs, rather than by software alone, as a complement to digital computation.

NG-CPSs will be cognitive-affective systems that not only optimize performance but also interpret human intentions, affections, and contextual meaning, while integrating physiological and behavioural sensing into system intelligence. From an epistemological point of view, NG-CPSs will move from pluri-disciplinary knowledge frameworks to post-disciplinarity and transdisciplinarity knowledge households. The transition to NG-CPSs is characterized by a movement from control-oriented engineering toward ecology-oriented system stewardship. NG-CPSs will increasingly act as cognitive collaborators, decision-shapers, and semi-autonomous actors in both industrial and societal domains. The need to shape these systems with the involvement of social stakeholders and consideration of civil knowledge will be stronger. As a major design principle of NG-CPSs, design for efficiency (performance optimization) will be complemented by the principle of resilience (robustness, antifragility, and fail-soft design). It is evident that the emerging intellectualization technologies and approaches, and the recognition that CPSs can be building blocks not only in Industry 4.0 and 5.0, but also in Society 4.0 and 5.0, also lend themselves to a significant change of paradigmatic features[42]. They may play roles in Education 4.0 too[43].

The strong self-designing and self-governing capabilities will increasingly allow CPSs to generate and refine their own architecture through meta-learning, evolutionary computation, and lifelong learning mechanisms. They will contribute to human-AI-environment co-evolution in which the interfaces indicated boundaries between users and systems will dissolve into co-adaptive collectives. Hybrid intelligence researchers posited that humans will not merely supervise but structurally participate in system intelligence. Some researchers have signalled the emergence of planetary-scale CPSs (for climate monitoring, smart energy grids, autonomous logistics, and global biomonitoring). This endeavour will transform CPSs into civilizational infrastructures rather than isolated technical systems. Human-like ‘intuitive’ pre-judgment will play as important a role as the facts-based logical and/or semantic reasoning. A decade ago, scholars introduced the concept of cyber-physical-social-thinking systems (CPSTSs), which explicitly integrates cognitive and anticipatory capabilities, enabling infrastructures to not only sense and respond but also reason, predict, and adapt in ways that emulate human-like intelligence[44].

Many researchers argue that cyborgs (cybernetic organisms) will represent a unique kind of NG-CPSs. They are also objects of various post-humanist visions and techno-utopian views, which are getting stronger nowadays. The concept of cyborgs is not new—it is an outcome of the progress in humanoid robotics[45]. Their significance lies in the fact that they can extend functionality and a range of capabilities and skills beyond what humans naturally have. NG-CPSs can provide the physical, cognitive, and social basis for their mass creation, and their development will have a new impetus from the establishment of agentic, embodied, and/or organic artificial intelligence technologies. Typical current representatives are (partial) surrogate cyborgs that efficiently replicate human upper and lower limbs, and inherent physical and cognitive capabilities[46]. Three other possible forms of their future implementations have already identified in the literature, namely (i) augmenting cyborgs (that are capable, for instance, of seeing invisible colours, detecting magnetic fields, hearing ultrasound, using telephoto, etc.), (ii) companion cyborgs (that serve as supporters and executors of daily activities), and (iii) reproductive cyborgs (that reproduce themselves for a purpose in strange environments even in non-resembling forms).

4. Conclusions

If we want to talk about NG-CPSs education, we must consider the famous saying of Heraclitus that “everything flows” (πάντα ῥεῖ) and that “the only constant in the universe is change”. The core message of this position paper is that a deep understanding and consideration of the nature of the changes in the foundational concepts, relations, and systems is indispensable to success. In addition, there is a huge, multi-faceted complexity caused not only by the latest trends, but also by the intrinsic complexity of engineering education, including SOEE as the ‘front yard’ of CPSs and NG-CPSs education. The changing relationship between humans and systems should be considered, together with the increasing level of cognitive capabilities (intellectualization) of engineered systems. CPSs are results not only of technological developments, but also of the extensive knowledge synthesis that happens in front-end sciences, systems engineering, systems paradigms, and civil society. This raises the need for post-disciplinarity and transdisciplinary thinking and methodologies, specifically in the context of NG-CPSs.

It can be concluded that the evolving system paradigm of CPSs entails that teaching/learning cannot be grounded merely in classical engineering disciplines (mechanics, electronics, and computer science). Instead, it presupposes a convergence epistemology, in which knowledge is organized around paradigmatic features of these systems rather than around disciplinary content. Therefore, an attempt has been made to conceptualize the epistemological foundations of CPSs as an integrative epistemic architecture rather than a collection of discrete disciplines. This brought the knowledge-spaces-oriented thinking (KSOT)[7] and associated methodological approaches[47] into existence, removing traditional disciplinary boundaries and facilitating novel epistemological modelling. Given technological, cognitive, social, ecological, and other uncertainties, education for CPSs must be oriented toward holism, resilience, adaptability, and instrumentality. NG-CPSs are supposed to operationalize ethical principles through (i) value-sensitive design, (ii) machine-readable governance, and (iii) algorithmic accountability mechanisms. They will require a reconceptualization of learning itself as a complex, adaptive system.

The operationalization of the new epistemological and methodological fundamentals is discussed in a follow-up paper, which offers a detailed discussion of the educational aspects of CPSs. It exemplifies and evaluates major epistemic and methodological innovations and discusses the essence and challenges of post-disciplinary and transdisciplinary CPSs education. It also extensively addresses the issues related to NG-CPSs as the object of education and as the agents of education and elaborates on the trends of pedagogic and andragogic progression. The discussion extends to the inclusion of artificial intelligence, the possibilities of progressive online education, and the challenges of andragogical approaches, focusing explicitly on the human side of education. It anchors the author's position by including six propositions that need further research by education research collectives with scientific interests in NG-CPSs education. Moreover, it also offers a reflection on some limitations.

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AI Use Statement

In the exploration phase of the research, Google Scholar with AI-modus was used to find published articles and documents related to the listed keywords and/or professional terms/phrases that are included in the section and subsection headings. In the finalization phase, the public version of Grammarly was used for grammatical corrections and style enhancement. No specific generative AI tools were used for data analysis, interpretation, or generation of scientific content. The entire text and all images have been generated by the author based on human semantics and not published elsewhere, not even in draft or pre-print repositories. Furthermore, all outputs were critically reviewed and edited by the author, who takes full responsibility for the integrity and accuracy of the work.

References

[1] Liu, Y., Peng, Y., Wang, B., et al., 2017. Review on cyber-physical systems. IEEE/CAA Journal of Automatica Sinica. 4(1), 27–40. DOI: https://doi.org/10.1109/JAS.2017.7510349

[2] Gunes, V., Peter, S., Givargis, T., et al., 2014. A survey on concepts, applications, and challenges in cyber-physical systems. KSII Transactions on Internet and Information Systems. 8(12), 4242–4268. DOI: https://doi.org/10.3837/tiis.2014.12.001

[3] Horváth, I., 2012. Beyond advanced mechatronics: New design challenges of social-cyber-physical systems. In Proceedings of the 1st Workshop on Mechatronic Design, Linz, Austria, 30 November 2012; pp. 1–20.

[4] Ragadhita, R., Fiandini, M., Al Husaeni, D.N., et al., 2026. Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches. Indonesian Journal of Science and Technology. 11(1), 1–26. DOI: https://doi.org/10.17509/ijost.v11i1.86298

[5] Ani, U.D., Al-Mhiqani, M., Tuptuk, N., et al., 2025. Socio-technical security modelling and simulations in cyber-physical systems: Outlook on knowledge, perceptions, practices, enablers, and barriers. IET Cyber-Physical Systems: Theory & Applications. 10, e70017. DOI: https://doi.org/10.1049/cps2.70017

[6] Wentzel, A., 2017. A Guide to Argumentative Research Writing and Thinking: Overcoming Challenges. Routledge: New York, NY, USA. DOI: https://doi.org/10.4324/9781315175676

[7] Horváth, I., Ábrahám, G., 2025. Transdisciplinary shifts in system paradigm-driven disciplines: Mecha-

tronics as an example. Transdisciplinary Journal of Engineering and Science. 16, 177–207. DOI: https://doi.org/10.22545/2025/00276

[8] Leon, C., Lipuma, J., 2025. From disciplinary silos to cyber-transdisciplinary networks: A plural epistemic model for AGI-era knowledge production. Journal of Systemics, Cybernetics and Informatics. 23(7), 102–115. DOI: https://doi.org/10.54808/JSCI.23.07.102

[9] Zhang, W., Wang, S., Sun, J., et al., 2024. Global evolutionary trends of the discipline of engineering education and their empirical implications. Engineering Education Review. 2(4), 145–160. DOI: https://doi.org/10.54844/eer.2024.0820

[10] Lin, J., 2017. The construction of China's new engineering disciplines for the future. Tsinghua Journal of Education. 38(2), 26–35.

[11] Asbjornsen, O.A., Hamann, R.J., 2002. Toward a unified systems engineering education. IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews. 30(2), 175–182.

[12] Michael, K., Pitt, J., Sargent, J., et al., 2024. Automating higher education through artificial intelligence? IEEE Transactions on Technology and Society. 5(3), 264–271. DOI: https://doi.org/10.1109/TTS.2024.3450694

[13] Baltà-Salvador, R., El-Madafri, I., Brasó-Vives, E., et al., 2025. Empowering engineering students through artificial intelligence (AI): Blended human–AI creative ideation processes with ChatGPT. Computer Applications in Engineering Education. 33(1), e22817. DOI: https://doi.org/10.1002/cae.22817

[14] Chen, B., Cheng, J., Wang, C., et al., 2025. Pedagogical biases in AI-powered educational tools: The case of lesson plan generators. The Social Innovations Journal. 30, 1–7. DOI: https://doi.org/10.31219/osf.io/zqjw5_v1

[15] Boon, M., Orozco, M., Sivakumar, K., 2022. Epistemological and educational issues in teaching practice-oriented scientific research: Roles for philosophers of science. European Journal for Philosophy of Science. 12(1), 16. DOI: https://doi.org/10.1007/s13194-022-00447-z

[16] Henriksen, D., Mishra, P., Woo, L., et al., 2025. The education doctorate in the context of generative artificial intelligence: Epistemic shifts and challenges to practical wisdom. Impacting Education: Journal on Transforming Professional Practice. 10(1), 73–79. DOI: https://doi.org/10.5195/ie.2025.485

[17] Hernández-de-Menéndez, M., Vallejo Guevara, A., Tudón Martínez, J.C., et al., 2019. Active learning in engineering education. A review of fundamentals, best practices and experiences. International Journal on Interactive Design and Manufacturing. 13(3), 909–922. DOI: https://doi.org/10.1007/s12008-019-00557-8

[18] Törngren, M., Grogan, P.T., 2018. How to deal with the complexity of future cyber-physical systems? Designs. 2(4), 40. DOI: https://doi.org/10.3390/designs2040040

[19] Horváth, I., 2025. Deriving manageable transdisciplinary research models for complicated problematics associated with next-generation cyber-physical systems: Part 3 - Constructing Research Models. Transdisciplinary Journal of Engineering & Science. 16. DOI: https://doi.org/10.22545/2025/00267

[20] Liu, Q., Tran, H., 2022. Exploring transdisciplinarity in engineering education and practice: A review of literature and existing initiatives. In Proceedings of the Canadian Engineering Education Association, Toronto, ON, Canada, 19–22 June 2022. DOI: https://doi.org/10.24908/pceea.vi.15953

[21] Lyngdorf, N.E., Jiang, D., Du, X., 2024. Frameworks and models for digital transformation in Engineering Education: A literature review using a systematic approach. Education Sciences. 14(5), 519. DOI: https://doi.org/10.3390/educsci14050519

[22] Keller, F., 2023. The concept of embodied human intelligence: Power and limits. Acta Philosophica: Rivista Internazionale di Filosofia. 32(1), 55–74.

[23] Nakajima, K., Hauser, H., Kang, R., et al., 2013. A soft body as a reservoir: Case studies in a dynamic model of octopus-inspired soft robotic arm. Frontiers in Computational Neuroscience. 7, 91. DOI: https://doi.org/10.3389/fncom.2013.00091

[24] Cangelosi, A., Bongard, J., Fischer, M.H., et al., 2015. Embodied intelligence. In Springer Handbook of Computational Intelligence. Springer: Berlin, Germany. pp. 697–714. DOI: https://doi.org/10.1007/978-3-662-43505-2_37

[25] Hauser, H., Ijspeert, A.J., Füchslin, R.M., et al., 2011. Towards a theoretical foundation for morphological computation with compliant bodies. Biological Cybernetics. 105, 355–370. DOI: https://doi.org/10.1007/s00422-012-0471-0

[26] Baldassarre, G., Granato, G., 2020. Goal-directed manipulation of internal representations is the core of general-domain intelligence. Journal of Artificial General Intelligence. 11(2), 19–23.

[27] Sitti, M., 2021. Physical intelligence as a new paradigm. Extreme Mechanics Letters. 46, 101340. DOI: https://doi.org/10.1016/j.eml.2021.101340

[28] Nakajima, K., 2020. Physical reservoir computing—An introductory perspective. Japanese Journal of Applied Physics. 59(6), 060501.

[29] Dodig-Crnkovic, G., 2013. The info-computational nature of morphological computing. In Philosophy and Theory of Artificial Intelligence. Springer Berlin Heidelberg: Berlin, Heidelberg. pp. 59–68. DOI: https://doi.org/10.1007/978-3-642-31674-6_5

[30] Zhang, P., Zhou, J., Chen, J., 2021. Form-finding of complex tensegrity structures using constrained optimization method. Composite Structures. 268, 113971.

DOI: https://doi.org/10.1016/j.compstruct.2021.113971

[31] Cheng, B., Li, M., Lin, M., et al., 2025. Mechanobiology across timescales. Nature Reviews Physics. 7(11), 621–644. DOI: https://doi.org/10.1038/s42254-025-00874-w

[32] González-Martín, M., Martínez-Ara, G., Ngo, J.T., et al., 2025. Synthetic mechanotransduction. Nature Reviews Bioengineering. 4, 236–249. DOI: https://doi.org/10.1038/s44222-025-00366-7

[33] Sadiku, M.N., Wang, Y., Cui, S., et al., 2017. Cyber-physical systems: A literature review. European Scientific Journal. 13(36), 52–58. DOI: https://doi.org/10.19044/esj.2017.v13n36p52

[34] Möller, D.P.F., 2016. Guide to Computing Fundamentals in Cyber-Physical Systems. Springer: Heidelberg, Germany. pp. 307–375. DOI: https://doi.org/10.1007/978-3-319-25178-3

[35] Horváth, I., Gerritsen, B.H., 2012. Cyber-physical systems: Concepts, technologies and implementation principles. In Proceedings of the Tools and Methods of Competitive Engineering, Karlsruhe, Germany, 7–11 May 2012; pp. 7–21.

[36] Qadir, J., 2023. Engineering education in the era of ChatGPT: Promise and pitfalls of generative AI for education. In Proceedings of the 2023 IEEE Global Engineering Education Conference, Salmiya, Kuwait, 1–4 May 2023; pp. 1–9. DOI: https://doi.org/10.36227/techrxiv.21789434.v1

[37] Banerjee, A., Venkatasubramanian, K.K., Mukherjee, T., et al., 2011. Ensuring safety, security, and sustainability of mission-critical cyber-physical systems. Proceedings of the IEEE. 100(1), 283–299. DOI: https://doi.org/10.1109/JPROC.2011.2165689

[38] Horváth, I., Rusák, Z., Li, Y., 2017. Order beyond chaos: Introducing the notion of generation to characterize the continuously evolving implementations of cyber-physical systems. In Proceedings of the ASME 2017 Computers and Information in Engineering Conference, Cleveland, OH, USA, 6–9 August 2017; pp. 1–14. DOI: https://doi.org/10.1115/DETC2017-67082

[39] Horváth, I., 2014. What the design theory of social-cyber-physical systems must describe, explain and predict? In An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations. Springer: London, UK. pp. 99–120.

[40] Sama, L.M., Welcomer, S.A., Gerde, V.W., 2003. Ecological citizenship: Principles, processes, and outcomes. Proceedings of the International Association for Business and Society. 14, 251–256. DOI: https://doi.org/10.5840/iabsproc20031432

[41] Colombo, A.W., Karnouskos, S., Bangemann, T., 2014. Towards the next generation of industrial cyber-physical systems. In Industrial Cloud-based Cyber-Physical Systems: The IMC-AESOP Approach. Springer International Publishing: Cham, Switzerland. pp. 1–22. DOI: https://doi.org/10.1007/978-3-319-05624-1_1

[42] Oks, S.J., Jalowski, M., Lechner, M., et al., 2024. Cyber-physical systems in the context of Industry 4.0: A review, categorization and outlook. Information Systems Frontiers. 26(5), 1731–1772. DOI: https://doi.org/10.1007/s10796-022-10252-x

[43] Jeganathan, L., Khan, A.N., Raju, J.K., et al., 2018. On a frame work of curriculum for engineering education 4.0. In Proceedings of the 2018 World Engineering Education Forum—Global Engineering Deans Council, Albuquerque, NM, USA, 12–16 November 2018; pp. 1–6. DOI: https://doi.org/10.1109/WEEF-GEDC.2018.8629629

[44] Ning, H., Liu, H., 2015. Cyber-physical-social-thinking space based science and technology framework for the Internet of Things. Science China Information Sciences. 58(3), 1–19. DOI: https://doi.org/10.1007/s11432-014-5209-2

[45] Özer, İ., Erden, Z., 2022. A novel approach to systematic development of social robot product families. International Journal of Social Robotics. 14(7), 1711–1729. DOI: https://doi.org/10.1007/s12369-022-00906-w

[46] Downey, G.L., Dumit, J., Williams, S., 1995. Cyborg anthropology. Cultural Anthropology. 10(2), 264–269. DOI: https://doi.org/10.1525/can.1995.10.2.02a00060

[47] Blouin, D., Al-Ali, R., Iacono, M., et al., 2021. An ontological foundation for multi-paradigm modelling for cyber-physical systems. In Multi-Paradigm Modelling Approaches for Cyber-Physical Systems. Academic Press: Cambridge, MA, USA. pp. 9–43. DOI: https://doi.org/10.1016/B978-0-12-819105-7.00007-6