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POSITION PAPER

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

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ABSTRACT

This position paper explores educational topics, methodological issues, and near-future prospects of learning approaches for next-generation cyber-physical systems (NG-CPSs). It first reviews major epistemic and methodological innovations and discusses a move toward post-disciplinary and transdisciplinary education. NG-CPSs are considered both as objects of education and as enablers of education. The paper critically examines the pedagogical inclusion of AI in CPSs education, the future of online learning, and the challenges of preparing for lifelong education. Six propositions are presented that highlight the importance of (i) exploiting the dual nature of NG-CPSs, (ii) thinking in knowledge spaces to foster disciplinary synthesis, (iii) integrating artificial intelligence paradigms into the evolution of NG-CPSs, (iv) including post-disciplinary research in education programs for NG-CPSs, (v) involving civil stakeholders strategically in NG-CPSs education, and (vi) implementing immediate andragogic innovation in the context of NG-CPSs. The paper argues that generations of CPSs increasingly influence public infrastructure, governance, healthcare, environmental sustainability, and daily life. It concludes that post-disciplinary and transdisciplinary CPSs education is essential and cannot simply be a linear extension of disciplinary engineering education. Therefore, it requires extensive exploration and constructive research.

Keywords: Educational Innovations; Post-Disciplinary Education; Transdisciplinary Education; Educational Position of CPSs; Pedagogic Concerns; Andragogic Concerns

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1. Introducing the Research Topic and the Approach of the Study

1.1. Research Topic and Its Importance

Cyber-physical systems (CPSs) have become a key technological paradigm of the digital age, combining physical processes, computational intelligence, communication networks, autonomous problem-solving, environment-aware integration, and human interaction. Their influence now extends well beyond traditional industrial automation and energy management systems. The rapidly evolving system paradigm is characterized by increasing autonomy, intelligence, connectivity, social interaction, personalization, and natural integration. This shift explains why CPSs are now dominant in areas such as smart infrastructure, agriculture, transportation, and environmental monitoring. They are also expected to revolutionize problem-solving and service delivery in everyday human activities such as healthcare, home care, sports, and education. As these systems develop toward next-generation cyber-physical systems (NG-CPSs), they fundamentally reshape not just engineering practice but also the epistemological foundations of engineering education. The anticipated emergence of NG-CPSs is directing focus toward understanding and addressing the challenges of managing post-disciplinary and transdisciplinary epistemologies in systems-oriented engineering education.

In response to these challenges, a growing body of literature emphasizes the need for post-disciplinary and transdisciplinary approaches in NG-CPSs education. Post-disciplinary education aims to transcend disciplinary silos by focusing on the synthesis of knowledge around problem contexts, creative processes, and system frameworks, rather than around established but disjunct fields of expertise. Transdisciplinary education goes further by involving actors outside academia—such as industry partners, public organizations, and civil stakeholders—in knowledge creation and learning processes. These approaches recognize that CPSs are not only technological artifacts but also socially embedded infrastructures whose design and operation require collaboration among multiple epistemic communities. The educational implications of this transformation are significant and not completely predictable.

Conventional engineering education has historically been organized along disciplinary boundaries, with knowledge domains such as mechanical engineering, electrical engineering, computer science, social science, human studies, and control theory treated as separate fields. However, NG-CPSs inherently transcend these boundaries. Their design, implementation, and governance require integrated understanding across technological, social, organizational, and environmental dimensions. Consequently, the traditional disciplinary model of education struggles to provide the epistemic integration and systems-level reasoning necessary for working with such complex, intellectualized, socialized, personalized, and naturalized systems. Another important development is the increasing role of the various forms and amalgamations of artificial intelligence, such as digital, corporeal, and combined AI, in both the development and the educational use of current and future CPSs. AI technologies enable sophisticated problem-solving, adaptive learning environments, cognitive digital twins, intelligent adaptive tutoring systems, and agent-based educational platforms [1]. At the same time, AI not only fundamentally changes the nature of CPSs themselves, but also the relationships among humans and systems. The relationship manifests in a dual evolution that, in turn, raises an important question: how should education prepare learners not only to design and operate CPSs but also to co-learn with intelligent systems that actively participate in knowledge creation and decision-making processes?

1.2. Methodological Approach

This study was conducted in line with a combined analytical and conceptual research methodology aimed at synthesizing existing knowledge, identifying emerging challenges, and formulating theoretically grounded propositions regarding the future of NG-CPSs education. The overall procedural flow of the study is shown in **Figure 1** as an activity roadmap. This differs from the blueprints of systematic literature reviews and surveys but underpins content generation for a position paper by extending from knowledge aggregation through semantic analysis to the formulation of forward-looking propositions. Three sources of knowledge have been considered: (i) the objective of professional contribution (in this case, the specific goals of the special issue), (ii) the major findings in the studied literature, and (iii) the author's prior research, innovation, and educational results. The purpose of the literature study was to obtain new insights, explore latent anomalies, and compose a semantic groundwork for argumentation based on real-life research experience. Procedurally, the flow of the knowledge processing activities included five interconnected phases: (i) factual exploration, (ii) conjectural anchoring, (iii) conceptual synthesis, (iv) formal rendering, and (v) reflective validation. Instead of presenting a consolidated theoretical model or empirical findings, the completed study has investigated a normative and strategic perspective on how educational systems should evolve to accommodate the characteristics of NG-CPSs. A strong intention was to align the paper's content and the propositions with the special issue's goals and to address its core questions in a prognostic manner.

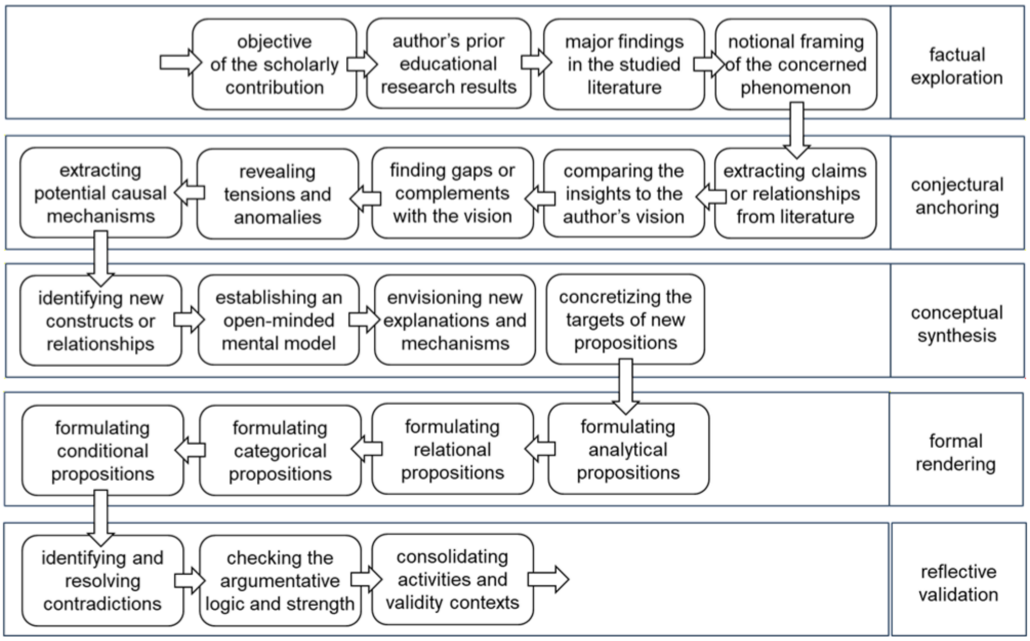

Figure 1. Overview of the procedural approach of the completed research.

The research sought to provide a coherent foundation for discussing the epistemological and pedagogical transformation needed in CPSs education. This is why the study has been structured around a specific procedural framework progressing from knowledge aggregation through conceptual interpretation to proposition formulation, and the methodological approach has combined elements of literature-based analysis, conceptual synthesis, and argumentative reasoning. Selected targets of analysis and discussion included pluri-disciplinary educational models, systemic challenges associated with CPSs education, AI-driven educational environments, the dual educational role of NG-CPSs, and the emergence of intelligent agents that actively take part in learning processes. Attention was given to the limitations of traditional discipline-oriented curricula in addressing the technological and functional complexity, integrative disciplinary nature, and pedagogical and andragogical affordances of NG-CPSs[2].

Based on these considerations, the work culminated in the conceptualization of a set of propositions that articulate the author's core claims. Rather than being invented arbitrarily, the propositions have been derived by the structured process depicted in **Figure 1** and formulated as self-explanatory suggestions for follow-up research and innovation. The six propositions stand for the novel conceptual contributions of the work and provide a foundation for future empirical research and educational innovation. They are offered in the belief that they can stimulate relevant research and support the rendering of reasoned claims that reinterpret or extend current knowledge. They are also intended to encourage scholarly debate and guide further investigation into the design of pedagogical and andragogical frameworks suitable for NG-CPSs. The author argues that the fundamental challenge of CPSs education lies not merely in keeping pace with technological change but in developing educational systems capable of sustaining epistemic responsibility, integrative reasoning, and lifelong learning in an increasingly complex and intelligent socio-technical world.

1.3. Overview of the Content and Structure

In a nutshell, this position paper delves into learning approaches for NG-CPSs, including educational topics, methodological issues, and near-future prospects. It also critically elaborates on the pedagogical inclusion of AI in education for and by NG-CPSs, the future of online engineering education, and the challenges of preparing for lifelong learning. It explores the epistemological foundations, pedagogical implications, and methodological requirements of educational innovation in this domain. Particularly, it examines the shift from discipline-centered engineering education toward post-disciplinary knowledge synthesis and transdisciplinary creative collaboration, while also considering the role of AI-enabled learning environments and lifelong learning frameworks. The central claim of this paper is that NG-CPSs education must evolve beyond incremental curriculum reform and, instead, adopt fundamentally new epistemic and organizational approaches capable of supporting complex, rapidly evolving socio-technical systems. Towards this end, some major epistemic and methodological innovations are first reviewed, and an underpinning concept of moving toward post-disciplinary and transdisciplinary education is discussed. Relying on the foundations summarized above, the paper addresses the emerging educational paradigm for NG-CPSs both as objects of education and as enablers of education. The analysis also explored how emerging concepts, such as knowledge-space-oriented thinking, post-disciplinary epistemology, and transdisciplinary collaboration, can address these limitations. It is important that the research adopted a position-building approach in which conceptual insights were translated into a structured set of arguments about the future of CPSs education.

The remainder of this paper elaborates on the above research perspective through a series of analytical and conceptual sections. Section 2 examines the broader context of education for cyber-physical systems, focusing on epistemic and methodological innovations that have already been seen in the field. It reviews existing approaches and highlights key challenges associated with the transition toward post-disciplinary and transdisciplinary CPSs education, including NG-CPSs as both objects and agents of education. Section 3 analyses key pedagogical and andragogical trends, including the pedagogical integration of artificial intelligence, the development of advanced online learning environments, and the increasing importance of lifelong learning in the context of rapidly evolving technologies. Based on these analyses, Section 4 formulates propositions that articulate the central position of the position paper on the future of NG-CPSs education. Finally, the concluding section synthesizes the arguments presented throughout the paper and reflects on the broader epistemological implications of educating for NG-CPSs.

2. Education for Cyber-Physical Systems

2.1. Major Epistemic and Methodological Innovations

The issue of education for CPSs at various academic levels and its implications for engineering and computer science education have been addressed in various documents, including the NASEM (2025) report [3]. This report highlights that the focus is usually on teaching technology integration, knowledge management, and systems engineering, but also emphasizes human, social, and sustainability issues. Following Henninger [4], experts argue that professionalism should complement engineering skills. Professionalism involves a responsible mindset and practice, aiming to understand societal impacts, manage risk concerns, respect norms and ethics, and make responsible decisions. Rahman [5] argued that knowledge alone is not enough for students to succeed. They must develop 21st-century skills like problem-solving, creativity, innovation, metacognition, and communication to thrive in today's world. Traditionally, problem-solving (critical thinking) skills were viewed as fundamental cognitive processes. However, the increasing importance of problem-solving in CPSs has made this perspective outdated.

To address these challenges, early CPS educators proposed epistemic and methodological innovations to improve the efficiency of education. Below, I discuss three of them that were applied successfully in practice. An often-experienced education issue is how to make clear to learners what systems belong to or do not belong to the category of CPSs, and how much they reflect a given paradigm of CPSs. Therefore, the first discussed didactic innovation relates to using paradigmatic system features (PSFs) for identifying and defining CPSs. The paper by Horváth and Gerritsen [6] proposed that CPSs can be characterized—and distinguished—uniquely by a set of PFSs and suggested using paradigmatic system feature profiles (PSF-profiles) for this purpose. These ideas imply a conceptual framework where the ontological essence of systems can be discussed without referencing their specific system manifestation features. **Figure 2** illustrates the process of building PSF profiles for various CPSs, based on a predefined comprehensive set of PFSs. Research has shown that this methodological approach can remain consistent even if the predefined sets need to change due to conceptual and technological developments. This methodological consistency and practical flexibility are vital for CPSs education in an era of rapidly evolving system manifestations.

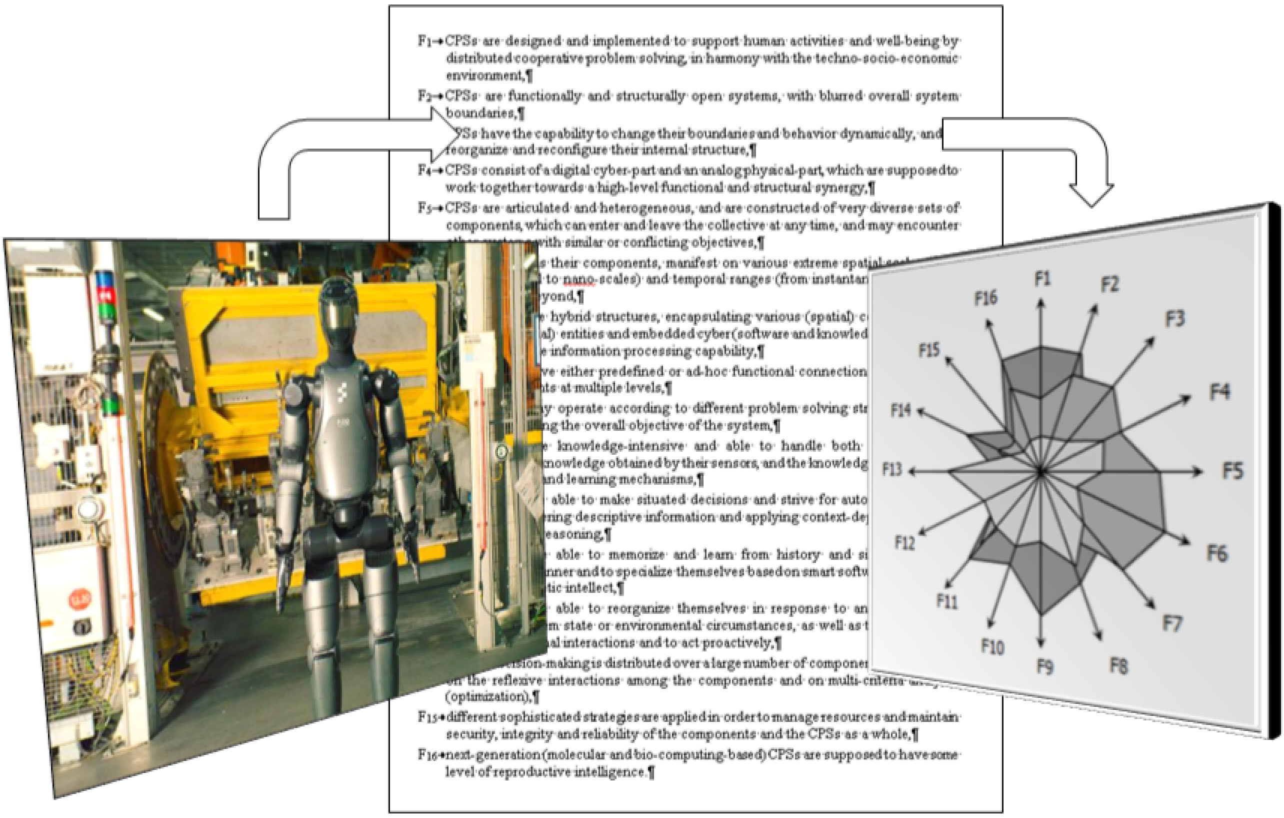

Figure 2. Introduction of CPSs relying on their paradigmatic feature profiles.

The second pedagogical innovation is rooted in the concept of post-disciplinary CPSs system engineering. In the background of this is the paradox recognized in terms of fostering holistic and prognostic systems thinking and being restricted to the traditional reductionist organization of educational programs. The operationalized approach concerns both the development of multi-year SOEE programs and the design of the content (theory and practice) for semester courses. **Figure 3** shows the strategy of top-down teaching/learning CPSs. Opposing the traditional disciplines-driven approach, it starts with the presentation and analysis of typical systems phenotypes and prototypes. Through the proliferation of CPSs for everyday professional applications, complementing the systems implemented for industrial use, the legacy of this has been evidenced. The competence-building process continues with learning the underpinning system paradigms, frameworks, and models.

Based on the related knowledge and competencies, learners can familiarize themselves with the functional, architectural, interoperation, control, and interaction elements of representative systems in the third stage. This is followed by the investigation of specific technologies, components, operations, implementations, verification, validation, security, and other constituents and characteristics. Together, these build the overall context in which discipline-specific knowledge is transferred, and competencies are developed.

This approach follows the procedural scheme of industrial conceptualization, design, and implementation of CPSs. At the same time, a purely holistic description of CPSs is not actionable for design, verification, certification, or operation.

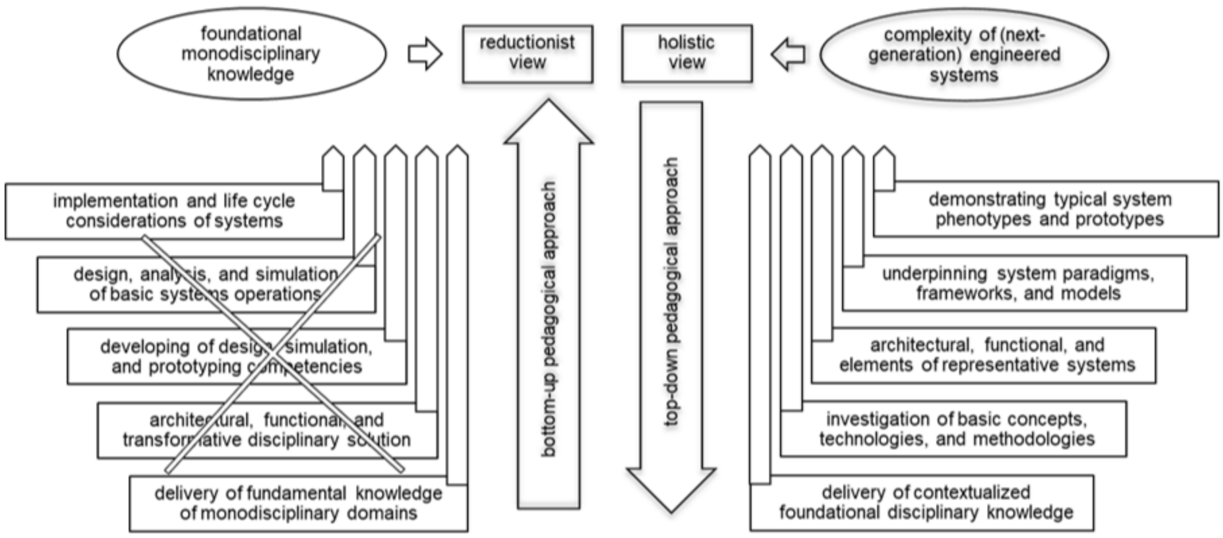

Figure 3. A holistic top-down approach (on the right) versus a reductionist bottom-up approach (on the left).

The world of CPSs is not modular in the same way as our institutions are. Having recognized it, the third innovative approach concerns the dynamic (selective) composition of study contents for educational programs and courses. This modularized course content composition approach contributes to the realization of freedom in personal objectives and choices at the strategic level, while addressing the evergreen issue of the rigid definition of educational content and paths. The essence of this institution-level approach is shown in **Figure 4**. The enabling technological concept is that of the educational program content warehouse (EPCW). It calls together compulsory, elective, and interest-designed educational modules that are of transdisciplinary, post-disciplinary, cross-disciplinary, interdisciplinary, and/or monodisciplinary nature. These include both theoretical and practicum modules. The epistemological, methodological, and logical relationships (precedence, belongingness, connections, preconditions, etc.) among the modules are captured by a content relationship map (CRM), which is updated in line with the existence and changes of modules. This regulates and guides the composition of individual learning paths for learners.

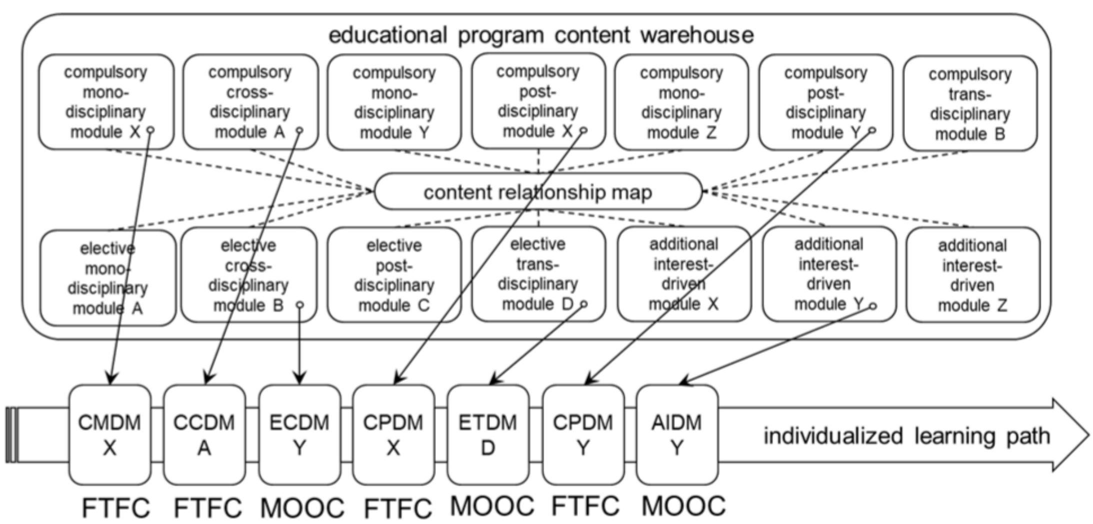

Figure 4. The framework for availing course content according to individualized learning paths.

The above practical innovations are important facilitators towards NG-CPSs education. They help reduce or even eliminate the recent dilemmas of CPS education that have appeared because of the involvement of too many disciplinary domains, which deal with both quantitative and qualitative, confirmed, and intuitive knowledge and methods. This variety must be taken care of not only in the conceptualization and design of CPSs, but also in future education.

The related literature also provides information on pedagogical possibilities and innovations that are important for CPSs education. For instance, Andruetto et al.[7] presented a postsecondary multidisciplinary CPSs course that provides an overview of how these systems contribute to sociotechnical change and adds a domain to all engineering disciplines. The course program is modularized, including dedicated modules to (i) CPS introduction and overview, (ii) AI for CPS and beyond, (iii) using systems thinking and system dynamics to understand CPS, and (iv) design project and presentations. Törngren and Herzog[8] investigated the relation between CPS, systems engineering, and the MIT-proposed CDIO (conceive–design–implement-operate) engineering education initiative to find ways of improving current CPSs education. They conclude that CPSs capstone courses should include systems engineering aspects such as (i) identification of stakeholders, their needs and concerns, (ii) defining a system concept in operation contexts, (iii) definition of the system requirements and architecture in multiple views, (iv) definition of an integration strategy to attain early feedback and minimize risks, and (v) select approaches for and implementation of verification and validation.

Oberer and Erkollar[9] have dealt with the issue of including cybernetic feedback loops in vocational education with a view to the rapidly transforming labor markets driven by automation, artificial intelligence, all-inclusive digitalization, and work-based learning. In this conceptualization, feedback loops allow the investigation of the dynamic interplay between education and work environments. Positive feedback loops can drive innovation by integrating emerging industry trends into curricula, whereas negative feedback loops function as regulatory mechanisms that correct outdated content and align training programs with contemporary labor market demands. As an example, they mention using sentiment analysis tools to revolutionize cybernetic learning by dynamically adjusting curricula based on student engagement and cognitive load.

Most probably, no one is against the fact that the current 'hotspot' of innovation in SOEE is its intelligentization by using the latest results of artificial intelligence research and development. It concurrently concerns the learners, educators, contents, processes, and environments, and creates a store of opportunities and a depot of challenges. The pace of progression is extremely fast but is not without issues and uncertainties. While we are still far from an exhaustive understanding and use of opportunities offered by generative AI technologies, the number of publications dealing with the development and exploitation of agentic AI technologies is rapidly growing, and hardcore researchers have turned their attention to the underpinning and exploration of embodied AI. The last-mentioned technologies may play a bigger role in systems engineering and education of NG-CPSs than any of the chronologically earlier technologies[10].

The review of Qian[11] shed light on the overall landscape of application of GenAI tools and identified (i) automated, immediate, and personalized feedback, (ii) continuous and formative assessment, (iii) learning immediacy and efficiency support, (iv) affective and social support, (v) cognitive support and prompt literacy, and development of critical skills (AI literacy, autonomy/agency, creativity, and critical thinking). He also highlighted concerns that are now taking shape, e.g., (i) technical, usability, and scalability limitations, (ii) quality and ethical concerns, (iii) AI literacy and overreliance concerns, and (iv) pedagogical challenges such as teacher role and control, motivation, engagement, and inclusivity issues. These potentially lead to the outsourcing of critical cognitive and metacognitive skills. As tasks for future research, they named exploring multimodal generative AI tools and fostering student-teacher-AI collaboration.

The study of Sunthonkanokpong[12] found that the characteristics of engineering education graduates in the 2020s should be characterized by the following: (i) acting as lifelong learners, (ii) ability to frame problems, (iii) putting problems in a socio-technical and operational contexts, (iv) dynamic/agile/resilient/flexible attitude, (v) high ethical standards, (vi) strong sense of professionalism, (vii) good communication skill, (viii) working with multiple stakeholders, (ix) possessing strong analytical skills, (x) exhibiting practical ingenuity, (xi) high-level creativity, (xii) possessing business and management skills, and (xiii) intrinsic leadership abilities. Nevertheless, the growing variety of engineering positions and the required competencies are not sufficiently projected to the different learners who completed NG-CPSs education. **Figure 5** sheds light on the diversity discussed above. The prevailing differences in expectations mean that educators must have the capabilities and capacities to develop matching, but rationally realizable, educational programs for all types of learners.

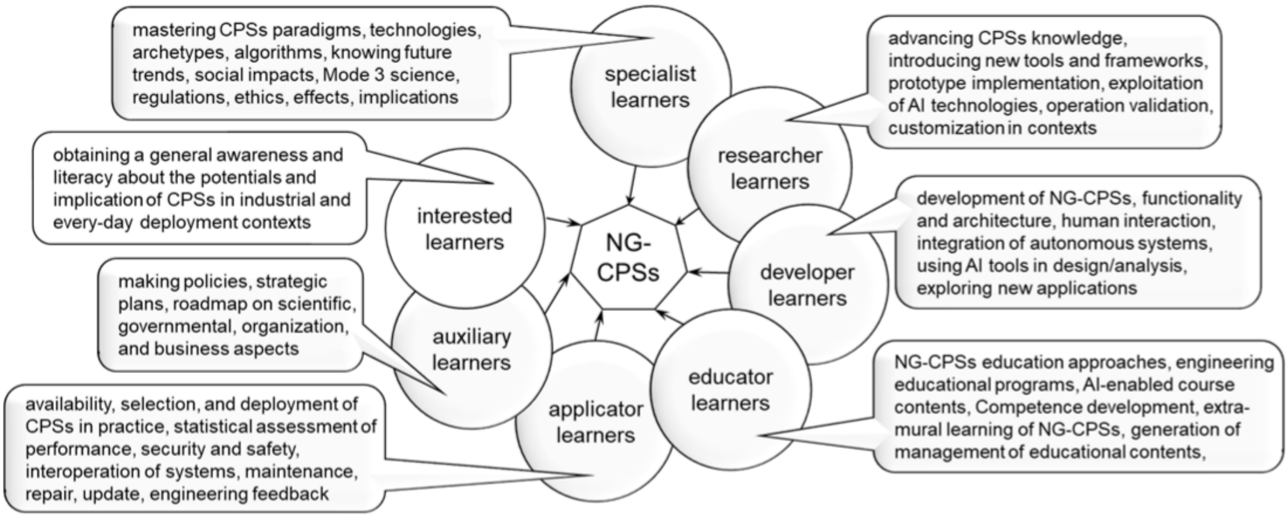

Figure 5. Diversity of NG-CPSs learners.

2.2. Marching towards Post-Disciplinary CPSs Education

Not differentiating systems (SOEE) and processes (POEE) centered forms, the paper by Mohd-Yusof et al. [13] presented a choice of universal characteristics expected of 21st-century engineering education. The selection includes (i) learner-centered organization and content, (ii) discovery-based or constructivist learning, (iii) thinking in a systems perspective, (iv) preferring competence to content orientation, (v) learning how to learn, (vi) involvement of scientific research methods, (vii) team-based problem solving, and (viii) preparation for the global economy. Most of these overlap with the expected outcomes outlined in the Engineering Programme Accreditation Manual, elaborated by the Engineering Accreditation Council in 2012. Though these universal characteristics apply to NG-CPS education, other additional characteristics are also needed. Among these latter, the most challenging one is deemed to be a post-disciplinary epistemological basis. Due to its holistic nature, it significantly deviates from current reductionist (mono-disciplinarily oriented) educational epistemology.

Post-disciplinary engineering education (PDEE) is not merely a curricular change but the mixture of: (i) operationalized art of epistemological knowledge synthesis and holistic delivery, (ii) intra-mural pedagogical transformation at educational institutions, and (iii) continuing learning according to an extra-mural, de-institutionalized strategy. Due to the required fundamental epistemic reorganization of educational objectives, structures, cooperation, and assessment practices, post-disciplinary education for CPSs cannot be realized through incremental curricular adjustments. Moving towards PDEE needs strategic decisions not only about new theoretical frameworks and methodological principles, but also about changing human attitudes and enforcing out-of-the-box thinking. Genuine post-disciplinary curricula cannot be established around disciplines or subjects.

Ready-made solutions for CPSs education are rarely found in the literature. On one hand, there are reports about changing curriculum structures, shifting focus from disciplinary subjects to challenge clusters, replacing course collections with learning trajectories, and moving from end-of-story degrees to stackable competence pathways. Reportedly, post-disciplinary pedagogy can be organized around systemic challenges (informatics, intelligence, systemization, complexity, energy, mobility, health, and climate) that cross traditional disciplinary boundaries. On the other hand, it is also recognized that various largely discipline-bound obstacles exist, such as: (i) institutional traditions and barriers, (ii) historical departmental structures, (iii) rigid accreditation frameworks, (iv) faculty identities tied to disciplines, (v) funding sources and models, and (vi) performance and formative assessments that hinder transformation. The transition may be limited not only by a lack of pedagogical insight but also by institutional inertia. Therefore, a move beyond disciplinary boundaries requires both epistemological and pedagogical innovation, as well as institutional and governance reform. From the learners' perspective, thinking in terms of learning trajectories allows them to develop competencies progressively across undergraduate, graduate, and lifelong learning stages. The main educational challenge of their post-disciplinary education is achieving collective epistemic synthesis and fluency across disciplines. A recognized risk is cognitive overload for all key actors (scholars, students, and engineers).

To understand and implement post-disciplinary NG-CPSs education, we need to grasp its fundamental features. The key question is how to shift epistemologically from reductionist, discipline-focused knowledge and thinking to holistic, post-disciplinary understanding. This question is essential because it involves not only identifying the required knowledge but also transforming our way of knowing. It requires an epistemological shift, not simply adjusting the workflow. As is well known, discipline-oriented reductionist thinking assumes that (i) systems are best understood by breaking them into parts, (ii) each discipline holds a piece of reality related to these parts, (iii) scientific rigor can be achieved by narrowing scope and tightening methods, and (iv) integration of information happens after analysis (if at all). Whereas, post-disciplinary holistic thinking assumes considering (i) the whole of a system, and not its parts, as a phenomenon, (ii) the boundaries between disciplines as connectors rather than separators, (iii) the appropriateness of methods of treatment as rigor rather than loyalty to a discipline, (iv) the primacy of synthesis instead of afterthoughts, (v) and the naturally modular, situated, relational, and layered nature of knowledge. The core epistemic flip happens by changing our interest from what a discipline can say about a system to what a system requires to be understood. Beyond translating concepts across fields, post-disciplinary work should also explore conflicts caused by different vocabularies and notice when the same is conceptualized at various levels.

From an epistemological perspective, it must also be recognized that the human mind naturally has a holistic view, but this perspective is broken down through externalization for various reasons, such as the need to manage complexities, the discrete nature of human languages, and the importance of thinking and acting with focus and within contexts. While this may sound abstract or philosophical, it eventually points to a solution. The goal should be to create a synergistic knowledge space (SKS) that humans inherently possess through their senses, awareness, and thinking. **Figure 6** illustrates the constitutive spaces that are fundamentally necessary to recreate SKS. These spaces overlap, and their boundaries become blurred due to the aspects of systems discussed. This is not about a messy compromise but about epistemic complementarity. The relationships that naturally exist among these spaces—or can be established purposefully with a system in mind—form pragmatic connections. The paper by Horváth and Ábrahám [14] operationalized the model shown in **Figure 6** in the development of a multi-year master's educational program for post-disciplinary mechatronics.

The shift from discipline-focused education to post-disciplinary education involves both epistemological and methodological innovations. As shown in **Figure 7**, a post-disciplinary educational knowledge synthesis should begin in the epistemological domain, followed by a transdisciplinary knowledge synthesis. These processes together support both the pedagogy-driven and andragogy-driven components of NG-CPSs and promote their development as lifelong learning. Moving toward post-disciplinarity is complex for several reasons: (i) any formal and precise account of naive holism must temporarily involve analysis, (ii) explaining reality requires using concrete concepts, making distinctions, unfolding over time, and temporarily deconstructing entangled phenomena, (iii) principal distinctions can only be derived semantically through abstractions from a whole, (iv) naive holism cannot be fully communicated or taught "holistically" in one shot due to human cognition and language limitations, and (v) it is important to recognize that part of this transition is social and institutional, as academia and professions tend to reward disciplinary identities. Holistic knowing involves the simultaneous presence and dynamic coordination of these challenging elements within lived experiences.

An added need for innovation is created by assessing post-disciplinary and transdisciplinary competencies. It has been recognized that the quality of knowledge reproduction alone is insufficient for evaluating the competencies required by NG-CPSs. It is foreseeable that assessment must shift from knowledge reproduction toward capability demonstration. The assessment practices must be transformed, and educators' and learners' assessments must focus on capability demonstrations through portfolios, scenario-based reasoning tasks, reflective learning narratives, system models, CPSs designs, and innovation potentials in societal and environmental contexts. On the other hand, contemporary literature only refers to this issue but provides neither detailed analyses nor tailored solutions. Additionally, learners need to be evaluated on their ability and extent to semantically integrate knowledge, reason with consequences, make justified design decisions, and reason under uncertainty. The theoretical framework and practical approaches of assessment transformation need further studies towards portfolio-based evaluation.

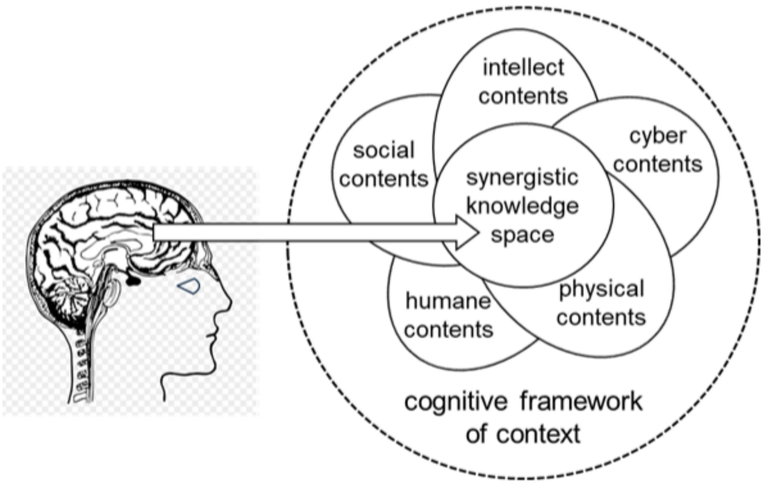

Figure 6. The constitutive spaces to consider when mapping the human mental model of systems to a synergistic knowledge space.

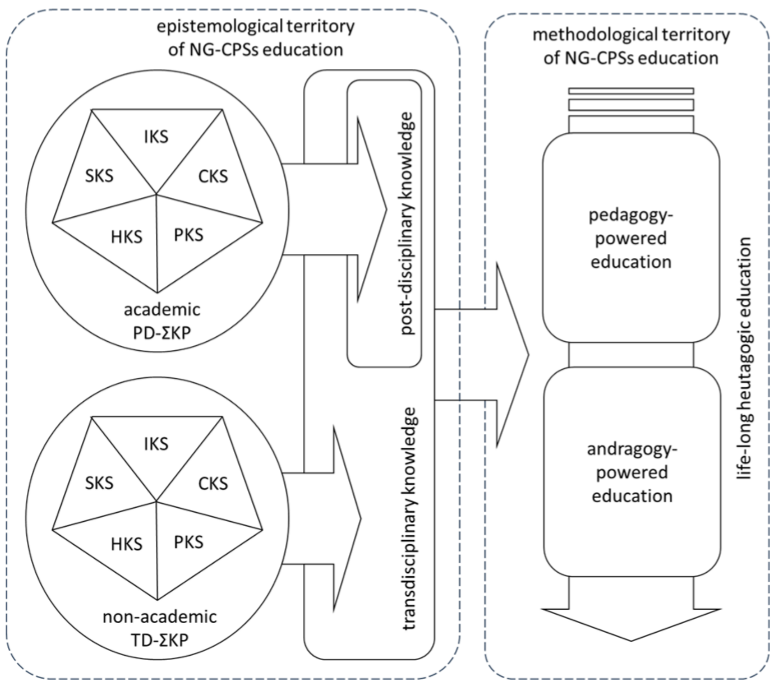

Figure 7. Epistemological and methodological aspects of NG-CPSs education.

Note: IKS = intellectual knowledge space, SKS = social knowledge space, CKS = cyber knowledge space, HKS = humane knowledge space, PKS = physical knowledge space, PD-ΣKP = post-disciplinary synthesized knowledge space, and TD-ΣKP = transdisciplinary synthesized knowledge space.

2.3. Stepping into Transdisciplinary CPSs Education

In a largely simplified form, transdisciplinarity is about the widest participatory knowing. I read somewhere that transdisciplinarity is a mode of orientation towards the wholeness of reality. In the context of CPSs education, its methodological essence is knowledge co-creation beyond academia. In daily practice, it means that industrial experts are not only "consulted" but involved as co-designers of content, meaning, values, and actions, and individuals of civil society are not only "input source" but co-authors of the knowledge itself. Opposing the assumptions of classical epistemology, transdisciplinary epistemology accepts that the knower is inside the system being known. It has several consequences, e.g., (i) knowledge becomes situated in context, (ii) perspectives are partial but complementary, (iii) objectivity becomes intersubjective coherence, and (iv) values, meaning, and conditions become part of semantics. In TDEE of NG-CPSs, such an epistemic standpoint is a functional requirement and an engineering necessity for learners, originating in the co-evolution of system knowledge across physical, digital, social, organizational, and environmental layers [15].

Transdisciplinary knowledge is not just "integration". While integration strives to assemble existing pieces into a bigger picture, synthesis strives to create a new epistemic object that did not exist before. Synthesis is purposefully oriented toward action in the world. Ultimately, transdisciplinarity blends academic theories and professional practices with gnoseological political constraints, local knowledge, lived experience, cultural meanings, ethical priorities, and ecological considerations into a new epistemology that reconfigures how the problematics can be seen and acted upon through its novel cognitive or practical framework. This makes civil society epistemically constitutive, rather than auxiliary, as holders of just gnoseological knowledge. That is, the role of civil society actors (the stakeholders) is much more than contributing as data sources, informants, or consumers. More specifically, civil entities typically can contribute three things that academia cannot guarantee or generate on its own: (i) problematics or problem constitution (not just problem information), (ii) normative orientation (social acceptability, cultural thresholds, ethical priorities as criteria of validity), and (iii) reality and viability testing of knowledge in natural contexts. The result is that epistemology is becoming ecological, combined with gnoseology, and knowledge is socially and systemically viable, and loaded with values.

CPS-relevant knowledge is inherently processual, relational, and lifecycle-based, requiring learners to think in terms of evolving systems rather than static artifacts. It also assumes the shift from courses to challenge clusters (e.g., autonomy, resilience, trust, sustainability), from degrees to learning trajectories spanning undergraduate to lifelong learning, and from fixed syllabi to adaptive content configurations. Co-production with non-academic actors brings the realism of justice in and opens the gate for a civilizational-level epistemic upgrade. Typical first step towards transdisciplinary engineering education (TDEE) is the involvement of company-specific projects in the knowledge acquisition process and collaborating with social stakeholders in external placements, assuming both competitive hard skills and complementary soft skills.

More advanced methodological forms of participation that go beyond "occasional ad-hoc consultation" or work in a "stakeholder engagement theatre" are (i) co-framing the problem space and the inquiry questions, (ii) co-producing high-fidelity system models, (iii) creation of hybrid (neither purely academic nor purely civic) knowledge spaces, (iv) co-defining success criteria and metrics, and (v) iterative experimentation in real-life contexts. The goal of these can be both the transdisciplinary development of an education program (program prototyping) and completion of a transdisciplinary project within the specified framework (experiential projects). Knowledge evolves through activation → feedback → reframing → redesign → reactivation cycles. Not only individual learners, but also collectives of society may learn cooperatively how to navigate a complex reality. By doing so, transdisciplinary knowledge becomes a shared cognitive asset for collective action.

When committed, civil society involvement in CPSs education fosters (i) more legitimate and lasting solutions, (ii) more resilient policies and systems, (iii) a more democratic epistemology, (iv) deeper cultural understanding and empathy, (v) earlier detection of systemic risks, (vi) faster learning cycles, (vii) higher adoption and trust, and (viii) motivation to continue learning and serving. In the context of transdisciplinary CPSs education, stakeholder-inclusive inquiry by learners is a lived experience in which knowledge is context-sensitive, action-guiding, subjectively revisable, and ethically charged. Its truth is judged by considering coherence, consequences, utility, and ethical viability. Learners who complete TDEE must get the skill to cross academic and societal boundaries seamlessly. While reductionism often confines observation to a single scale, learners must be prepared for holistic thinking that moves, on the one hand, between the physical micro, meso, and macro levels, and, on the other hand, between the symbolic, semantic, pragmatic, and apobetic layers of interaction, also considering how these levels co-constrain each other. Moreover, such large-scale engagement requires tailored educational policies, collaborative frameworks, and pedagogical approaches, which cannot be directly derived from current practices and are somewhat premature. How to embed society in engineering universities, or how to make society an innovative engineering university? A long journey lies ahead.

My above argumentation may be read as theoretical or abstract. This reflects the current stage of understanding and progress. The bottom line is that SOEE, including post-disciplinary and transdisciplinary CPSs education, cannot be squeezed into universal frames. They have no universal goals or approach, not only because of their orientation towards different educational objectives (domain competencies), but also because of their guidance by the different educational philosophy principles: (i) essentialism, (ii) progressivism, (iii) existentialism, (iv) behaviorism, and (v) constructivism. Each combination of objective and philosophy provides a unique perspective on why, what, and how to learn and teach. Pistrui et al. [16] reported that academic institutions in the USA offer three paths to prospective engineering students: (i) four-year bachelor degrees with "R1" research focus (typically following on to postgraduate degrees and careers in research or academia), (ii) two-year associate degree (community college) (typically leading to a career based on a technical skill or trade), and (iii) four-year bachelor degree with industry focus (typically leading to careers in technically-based industries). To move towards a transdisciplinary framework, they proposed a new model for the third path that focuses on the talent pipeline and aims to foster broad industry involvement and interest. Transdisciplinary education also raises the idea of technology-supported cross-cultural learning. To support this, Shadiev et al. [17] developed and operationalized an AI-based X-Cultural App to support cross-cultural learning in authentic environments.

2.4. Next-Generation Cyber-Physical Systems as an Object of Education

In the current education, CPSs typically appear as disciplinarily heterogeneous artifacts, and are addressed by cross-disciplinary pedagogical strategies, where the role of integrator discipline is played by software engineering, data/knowledge science, or cognitive engineering. However, NG-CPSs will not be advanced technological and functional artifacts and will not be merely a deterministic body of knowledge to be studied anymore. They will manifest as epistemic boundary objects. As such, they connect theory and practice, integrate technologies and problem-solving, and bridge disciplines and stakeholders. In addition, based on digital access and online observation (participation) opportunities, NG-CPSs can also serve as learning laboratories and safe failure demonstrators that reshape how knowledge is produced, acquired, validated, and applied. This means that NG-CPSs should be thought of simultaneously as enabling agents of education and a rapidly changing field of post-disciplinary SOEE. In the role of epistemic boundary objects, NG-CPSs will be a "veterinary horse that is susceptible to all possible diseases", redefining the object of education itself. Based on their intellectualization, socialization, and personalization, they will also be educators, and not only used as accessible tangible manifestations, experimental spaces, demonstrative application cases, experiential digital twins, or simulated (future) realities. Consequently, CPSs education must train learners not only to understand systems, but to co-learn and co-create with NG-CPSs.

The development of NG-CPSs requires a shared understanding across heterogeneous epistemic communities, making them ideal focal points for post-disciplinary learning. As boundary objects, they can mediate between knowledge spaces and methodological approaches. As tangible manifestations, they can connect academic theories and best practices/experiences in post-disciplinary education. Studies have been published on using current CPSs as experimental knowledge environments. Through digital twins, simulations, and synthetic data generation, learners can evaluate hypotheses or derive conjectures, explore emergent behavior and failure indicators, and experience the consequences of design decisions in controlled yet realistic settings. Failure becomes a productive learning mechanism rather than a risk to be avoided. Also, they have been used as catalysts among academic and non-academic stakeholders in early TDEE. It can be assumed that NG-CPSs will be even more capable of enabling shared understanding across disciplines and stakeholders, while bridging the gap between front-end theory and innovative practice. In addition, NG-CPSs will constitute ethical learning arenas. By embedding constraints into system behavior, and addressing value conflicts, de jure and de facto regulations and norms, algorithmic accountability, and societal impact-driven reasoning, learners confront ethical trade-offs directly through design and operation. Responsibility will be taught and learned not abstractly, but through design and system consequences.

Discussed in the literature is that the competencies of educators and learners should receive equal emphasis in innovations for SOEE, and they need to be orchestrated. This is also a valid expectation for NG-CPSs education, where many white spots exist. Based on synthesizing five established frameworks, Xu [18] proposed an integrated competency model for engineering teachers, which amalgamates technical, pedagogical, professional, and ethical aspects. This competency model suggests that: (i) pedagogical skills, (ii) social capability, (iii) AI integration capability, (iv) technological adaptability, (v) industry collaboration, (vi) teacher motility (active progression), and (vii) specialized knowledge aggregation is needed at the same time to cope with the challenges of modern engineering education. Referred to as "cyber-physical learning", a new form of learning is discussed in the paper of Sockalingam et al. [19]. It is described as a learning environment in which both remote cyber students and face-to-face physical students can learn and interact effectively, seamlessly, and synchronously in the same class. Beyond blended/hybrid learning, this environment leverages emerging technologies, such as immersive technology, telepresence robotics, learning analytics, and artificial intelligence, to improve learning outcomes and enhance student engagement.

2.5. Next-Generation Cyber-Physical Systems as Agents of Education

Educational environments depend on the physical, social, and technological contexts in which learning occurs. Traditionally, they were passive systems, while recent developments attempt to transform them into active systems. The system paradigm of CPSs plays a key role and enables this transformation. For instance, Gallon et al. [20] provided a holistic vision of what they regarded as the University 4.0, analyzed the role of ECPSs in this context, and proposed a generic layered architecture for their three different instantiations (classroom, course, and curriculum ECPSs). In addition to being objects and enablers of education, NG-CPSs will increasingly function as agents of education. This is stimulated by and anchored in the advances in artificial intelligence research, agentic architecture development, and embodied cognition, which enable CPSs to actively take part in learning processes. The obvious trend is the proliferation of (i) CPS-based tutors and coaches, (ii) agentic learning companions, and (iii) resolute instructors for large-scale CPSs. AI-powered ECPSs may offer a wide range of functions, including (i) demonstrative case CPSs, (ii) adaptive tutor CPSs, (iii) assessment agent CPSs, and (iv) co-learner CPSs, as the most fundamental ones. The dual role of CPSs discussed so far is a fundamental shift from education about systems to education with systems. It not only redefines the human-technology relationship in learning but also necessitates the elaboration and introduction of new mental models, ethical frameworks, and governance mechanisms. The effects are far-reaching. As discussed by Bachir et al., combined with AI, it may convert current universities into fully online, autonomous universities [21].

The current hot topic is functionality and realization of agents of education, relying on the paradigm of CPSs and the technologies offered by agentic artificial intelligence research. CPS-based educational agents can support personalized learning trajectories, adaptive feedback, and reflective scaffolding [22]. They can monitor learner progress, suggest resources, generate formative assessments, and facilitate collaboration. In more advanced configurations, CPSs function as learning partners that co-explore problem spaces with learners. Agentification of CPSs facilitates a transition from autonomous reactive systems to cooperating initiative-taking systems, among other things, in education. This represents a change in the basic assumptions (i.e., a paradigm shift concerning both the foundations and the manifestations) of artificial intelligence. To be truly agentic (i.e., capable of taking meaningful actions based on its own reasoning), an AI-based education system needs the capabilities to understand the learner's goals, needs, and preferences, and to provide reliable guidance and adaptive support for their learning.

Agentic systems are supposed to be capable of perceiving environments, reasoning about complex situations, planning their actions aligned with specific goals, and executing decisions. Designing agentic AI-based educational systems involves creating components that support autonomy, personalized learning, and engagement. They are also blurring the line between research, development, and education.

In a non-peer-reviewed manuscript, Khalid et al.[23] studied how agentic AI can serve in education as a learning partner or a peer facilitator of students (rather than simply delivering information). They prognosticated that agentic AI systems will be as dominant in the field of educational platforms as in healthcare, systems engineering, e-commerce applications, cybersecurity systems, and large-scale network architectures, while improving efficiency, reducing manual workload, and helping in making more informed decisions. This resonates with the findings of Mosly[24]. However, while supporting personalization and engagement is promising in adaptation to learner profiles and enables participation in collaborative tasks, concerns are raised concerning (i) the scale of dependence, (ii) AI literacy training for educators, (iii) understanding situated agent behaviour, (iv) possibility of comprehensive ethical/moral auditing, (v) human-AI intuitive co-design, and (vi) forming correct mental models.

Frequently argued that the evolution of agentic AI represents not merely technical advancement but also a fundamental reconceptualization of human-machine relationships, with profound implications for how intelligent systems will operate and integrate within society. Though the computational goals of agentic AI are stated on technical implementation level, it is hardly discussed in the literature (i) how agent architectures can be tailored to educational functionalities, (ii) what specialized perception modules and components are needed for agentic education support systems, (iii) what sort of dynamic world modelling capabilities are necessary, and (iv) what goal management, activity planning, and action execution mechanisms are necessary[25]. Also, an open issue is how specialized agents can work in concert in a broadly distributed dynamic learning environment to enable initiative-taking (proactive) collegial behaviour. The recommendations for creating agentic AI-based educational systems consider a combination of disciplinary specificities, educational theories, AI capabilities, and general principles of human-computer cooperation. They assume research-backed practices to guide the conversion of the knowledge from these sources into effective, autonomous, and personalized learning environments. The core architecture of an agentic system typically encompasses five fundamental subsystems that operate in a coordinated harmony: (i) perception modules for environmental sensing, (ii) world modelling capabilities for representational understanding, (iii) goal management systems for objective prioritization, (iv) planning mechanisms for action sequencing, and (v) execution frameworks for implementing decisions.

Like AI agent architectures, agentic CPSs educational frameworks include four major components, namely (i) memories (short-term and long-term), (ii) tools (timers, calculators, interpreters, converters, effectors), (iii) actions (triggers, moderators), and planning (breakdown, reflection, self-evaluation), designed to enable perception, reasoning, decision-making, and interaction collaboratively. Educational AI agent architectures are objects of ongoing research because they leverage transforming possibilities in technology and beyond[26]. Garzón et al.[27] examined the current research trends, the impacts of generative AI tools, the range of benefits, and the foreseen challenges. In agreement with others, they found that the benefits includes enhanced learning outcomes, personalized instruction, and increased student motivation, while the deficiencies are such as the need to adapt existing pedagogical models, develop new student competencies, overcome teachers' resistance to using AI systems, ensure students' ethical use of AI, resolve digital dependency these systems can generate, and address other ethical, social, and technical concerns. No matter how comprehensive an AI inauguration framework is, its success depends on careful implementation and the collaboration among educators, researchers, and policymakers to ensure meaningful and equitable outcomes.

3. Trends of Pedagogic and Andragogic Progression

3.1. Pedagogic Inclusion of Artificial Intelligence

Like CPSs, artificial intelligence (AI) technologies should also be understood as both the object of the curriculum and the support of educational practice, as **Figure**

8 shows. Therefore, integrating the latest AI into SOEE is a Janus-faced complex issue. As literature shows, there are still several obstacles and gaps in both perspectives [28]. Some authors reduce it to the intelligentization of the systems developed to support education. Anyway, the word is used confusingly in literature in my view, since intelligentization as a goal of cognitive engineering is radically ambitious, while largely underdefined both ontologically and functionally. Since pedagogical systems eventually are problem-solving systems, I believe that the term 'intellectualization' better describes the realistic and feasible goals of education cyber-physical systems (ECPSs) development. Intellectualization is the process of equipping ECPSs with intellect and capabilities for educational interaction, whose ultimate core is computational problem-solving, i.e., making them able to possess, explore, aggregate, synthesize, share, and exploit knowledge and to reason with it towards fulfilling operational objectives [29]. In this sense, intellect is a computational subset of overall human intelligence. Intellectualization is conjointly about the rational content (system knowledge) and the transformational agents (reasoning mechanisms) [30].

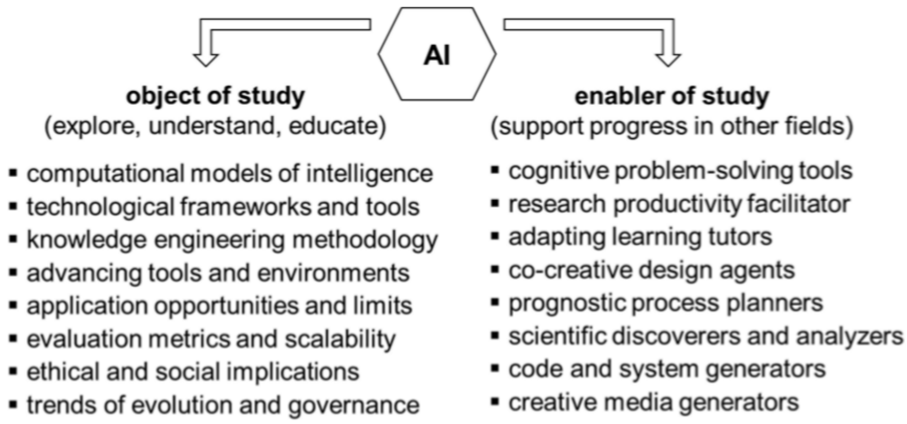

Figure 8. Dual role of AI in CPSs education.

Intellectualized systems show various self-* features, such as self-awareness, self-learning, self-reasoning, self-control, self-adaptation, self-evolution, and self-reproduction. These features make them nondeterministic, goal-oriented, context-aware, causality-driven, reasoning-enabled, and retrospectively, inductively or abductively learning systems. The role of AI in higher engineering education has been interpreted from the perspective of both constructivism and connectivism. In the former perspective, AI facilitates the realization of adaptive and interactive learning environments that promote experiential and autonomous learning. In the latter perspective, AI contributes to selective access to knowledge across networks, supports learners in accessing the sources of information, and promotes constructive collaboration. Raikoti et al. [31] discussed an interesting aspect of involving AI in the daily educational practice. They argued that AI should be treated as a supportive source of data collection instead of totally replacing our daily education process.

The challenge of building ECPSs has been addressed from several perspectives, including focus, content, process, system, and context. Selvaraj et al. [32] proposed a multiple-layer model of ECPSs in which the layers enable judgments about the adaptation of the educational process and the implementation of activities based on data gathered from the physical and cyber educational environment. Hayashi [33] assumed that CPSs as authentic learning environments (i) detect actual human activities and global environmental changes, (ii) clarify the process and its essence placed into context), (iii) connect learners to places where real environmental change is occurring, and (iv) provide learners with real-world experience in knowledge utilization. However, research papers dealing with technical, functional, and operational issues are still scarce.

3.2. Forward-Looking Online Education

The concept of blended learning has been known as a less formal educational framework in SOEE for a long time. It makes it possible for learners to learn partly through online delivery of content with some element of student control over time, place, path, and/or pace, and partly in directly supervised in-house courses [34]. As part of blended learning, the term online learning is used interchangeably with electronic learning, cyber learning, and virtual learning in the related literature. Just as the emergence of virtual reality environments created opportunities for virtual learning, AI systems are creating new opportunities for permanently assisted education (including simulation-based learning of CPSs). Virtualization, intellectualization, and agentification create potential for computer simulation of real system operations, as well as for the implementation of thought experiments. These are important facilitators towards NG-CPSs education. There are several epistemological, procedural, pedagogical, communal, and assessment requirements for systems and methods for pure online education.

The most important epistemological ones are (i) providing multi-modal (spoken, written, graphical) interaction opportunities, (ii) adjusting the difficulty level of topics and tasks as needed, (iii) synthesizing best practice knowledge for inter-systems sharing, and (iv) integration of external online tools, media, and resources, and (v) assisting the preparation of intermittent/output documents. Some representative procedural ones are: (i) construction of thematically modularized educational contents, (ii) setting up plans for attaining goals based on the learners' own pace, learning style, and level of understanding, (iii) tracking progress over time and areas where more support is needed, and (iv) assessment of a learner's current knowledge and competencies. Pedagogical requirements for functions include (i) proposing content, approaches, and resources according to interests, (ii) monitoring sentiment (emotional tones) and stimulation of emotional states, (iii) fostering active recall, spaced repetition, and constructive application, and (iv) enforcing a reflective learning practice throughout the learning journey.

Communal expectations are: (i) acting as a peer in conversations, answering questions, and clarifying difficult concepts, (ii) providing long-term motivation/engagement support, (iii) supporting real-life interaction and socialization with other learners and potential academic and civic advisors, (iv) creating a virtual/real community of learners with shared interests, and (v) and providing context or situation dependent human teacher/mentor involvement/intervention. Lastly, evaluative functional expectations are (i) conducting topical and formative assessment in line with the activity plans, (ii) managing a learning performance analytics/prediction dashboard, (iii) ensuring privacy, safety, and confidentiality by adhering to regulations, (iv) enforcing ethical principles, fairness, and inclusivity, and (v) running system self-learning and self-improving algorithms. The sheer number of items in the above restricted overview illustrates the complexity of a purely online educational strategy.

3.3. Challenge of Andragogic Approaches

NG-CPSs education spreads not only intellect and space, but also in time. However, this latter aspect has not received sufficient attention in the related literature, whereas issues related to adult education are often addressed. **Figure 9** has been designed to summarize the main aspects and concerns towards life-long CPSs education. There are three influential changes in the procedure: (i) the locus of education (intra-mural, combined-mural, and extra-mural), the maturity of the learner (child, junior, and adult), the framework of education (program-driven, capability-driven, and interest-driven), and the purpose of education (engagement, cultivation, and realization). With growing maturity, the capability of choosing education goals and methods, and the learning autonomy are increasing, potentially leading to self-managed autonomous learning. Experience with education and the acquired competencies increase the rationality of defining goals and choosing personality-proper approaches [35]. These factors appear in holism, but that has been decomposed for pragmatic reasons. This non-ontological decomposition has defined the domain of engineering pedagogy, andragogy, and heutagogy [36]. The complementary nature of these can be understood by considering the factors mentioned above.

Pedagogy is deterministic in its objectives—it focuses on scholarly attributes and the formative part of education. In addition to disseminating knowledge of disciplinary fields, it nurtures competencies based on well-defined educational programs and courses. Although some experts reject this dichotomy. Andragogy is about the professional orientation and progression of adults. In the conceptualization of Knowles [37], andragogy operationalizes six principles to guide adults in continuing education (and educators who want to adopt andragogical teaching methods). The principles are (i) adult learner experience, (ii) readiness to learn, (iii) orientation to learning, (iv) self-development concept,

(v) motivation to learn, and (vi) active learning conduct. While the theories, methodologies, and practices of pedagogy are presented comprehensively and consistently in the literature, andragogy has received much less attention [38]. Therefore, its contribution to the field of SOEE appears less elaborate and consolidated. Even though it (i) is confronted with many different real-life situations of learners, (ii) is supposed to cover a longer period of human life than pedagogy, (iii) may be based on different conceptual frameworks and organizational constructs, and (iv) may benefit from approaches not routinely used in institutionalized education, this situation exists.

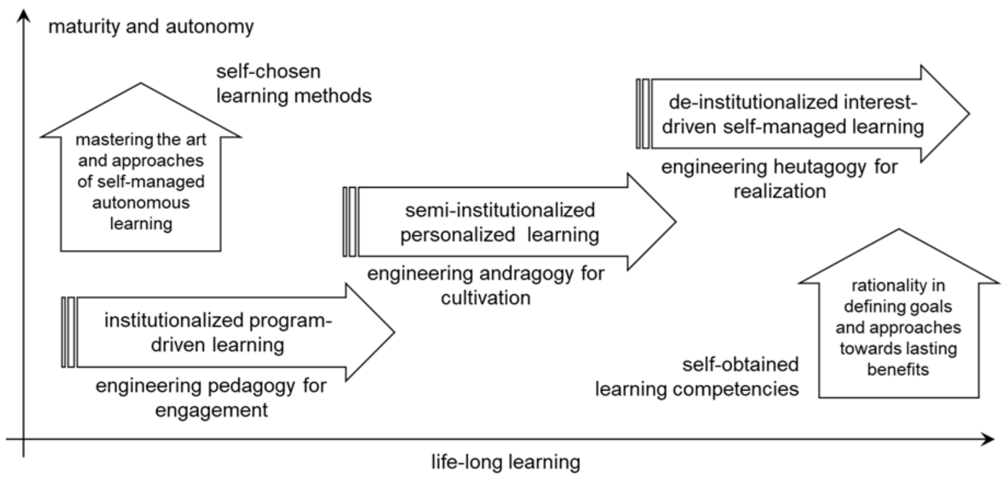

Figure 9. The main concerns of preparation for lifelong learning.

Andragogical theory assumes foregrounding self-direction, experiential capital, and reflexive professional identity. It puts the emphasis on reflexive professional identity, even if some adults prefer structured, teacher-led learning environments. It posits that adult learners are trained to (i) recognize new professional trends, (ii) critically handle engineering novelties, (iii) set challenging but forwarding learning goals, (iv) manage uncertainty related to real-life situations, (v) recognize current and future possibilities and threads, (vi) find cooperative peers and advisors as needed, (vii) eliminate uncertainties caused by incomplete information, (viii) utilize experiential capital in various contexts, (ix) reflect on social and ethical responsibility, (x) handling mandated learning contexts, and (xi) negotiate human-AI boundaries. Andragogy treats the forms of ambiguity as didactically productive, not something to be eliminated. In addition to content, it also addresses autonomous learning methods and critical personal assessment of knowledge, to prepare for life-long learning [39].

Although they are not accepted universally, I presume that Knowles' heuristic (and somewhat idealized) assumptions concerning the foundational concepts of continuing learning are valid for framing post-institutionalized learning in CPSs. However, research should delve deeper into the reasons for learning, self-directedness, experience impact, orientation to learning, readiness to learn, and orientation of learning in the context of NG-CPSs. Currently, hardly any publications seem to deal with the practical operationalization of these principles. Despite andragogy underemphasizing communities of practice, social identity formation, and apprenticeship models, it is not known if there are obstacles in terms of combining its conceptual framework with other adult learning frameworks, such as Mezirow's transformative learning and Kolb's experiential learning theory [40].

Coined by Hase and Kenyon [41], heutagogy has become an alternative theory of andragogy, partially overlapping with it. Also referred to as self-determined learning or double-loop learning, heutagogy is grounded in five key principles that guide its implementation and distinguish it from other educational approaches: (i) learner agency, (ii) self-efficacy and capability, (iii) metacognition and reflection, (iv) non-linear learning, and (v) learning how to learn. In practice, it is an advanced educational approach according to which learners take full control of their learning journey by deciding what, how, and when to learn. It focuses on developing problem-solving abilities, critical thinking, and adaptability, making it highly relevant for the digital age and an ideal strategy for complex digital environments. Why heutagogy differs from andragogy is that learners are supposed to go beyond self-directed/oriented learning to become autonomous, capable lifelong learners by setting their own goals, determining the entire process, choosing methods, developing deep capabilities, and self-reflecting on their own experiences, with educators acting as facilitators [42]. Learners are also supposed to be mature enough to question underlying assumptions, practice self-reflection, and develop new strategies and a deeper understanding. The learning path is taken as an adaptive route rather than a straight one, and the educator does not dictate the curriculum but motivates, guides, and supports. In addition, several personal abilities and soft skills have been defined for CPSs learners, for instance, background experience, target orientation, intrinsic motivation, personal management, resource allocation, action readiness, critical reflection, and fulfilment satisfaction.

3.4. The Human Side of Education Approaches

The human side of NG-CPSs education is about shifting from training technical problem-solvers to forming reflective, responsible system designers who can integrate knowledge across disciplines, reason under uncertainty, work with and for people, and exercise sound judgment in complex socio-technical worlds. At the same time, I have observed that mainstream CPSs education literature treats the "human side" as a soft add-on rather than as the backbone that basically makes the technical stuff usable, sustainable, and ethical. Furthermore, it does not reflect the trend of shifting from teaching systems to supporting learners who want to develop and build NG-CPSs to meet abundant psycho-socio-ecological requirements. This is contradictory because many researchers have claimed that pedagogy must move beyond pure technical mastery and include understanding users, operators, and stakeholders.

The educators currently engaged with the latter are not at home with systems science, whereas HW/SW/CW engineers hesitate to give up their stable, modular, and discipline-bounded traditional thinking, methods, and knowledge. The sources of fear are (i) working with knowledge that is at least interdisciplinary, contextualized, probabilistic (vague or uncertain), (ii) abandoning linear pipeline methodologies to prefer iterative and reflective practice, (iii) accepting failure and debugging as core shared learning modes, and (iv) complicatedness of the framing → modelling → prototyping → testing → reflecting → revising → communicating → repeating → deploying workplans. It seems systems thinking, risk awareness, and ethical reasoning receive less attention than collaboration across cultures and disciplines, redistribution of responsibility between humans and systems, sense-making in complex, ambiguous, and safety-critical situations, and designing for human dignity and emotions. However, this may not necessarily be true, as even those who are tech-savvy struggle to keep up with the rapid pace of technological advancements.

4. Anchoring the Position: Propositions

Based on the major findings, the following propositions have been derived and offered for concerned researchers of CPSs pedagogy and andragogy: (i) NG-CPSs will not be only the object of learning, but also the cooperative agents of learning, (ii) discipline oriented thinking in current CPSs education should be replaced by KSOT, (iii) education should be prepared for the new paradigms of artificial intelligence technologies, (iv) post-disciplinary education for NG-CPSs should start with knowledge synthesis by post-disciplinary research, (v) TDEE including civil stakeholders should be addressed not only from methodological but also from epistemological and responsibility aspects, and (vi) in addition to the educational innovations, andragogic innovations are equally needed. The propositions have been formulated so they can be quoted verbatim and defended as the paper's core intellectual contribution. Towards this end, I explain why a proposition follows from the preceding descriptive and analytical sections, provide explicit argumentative (logical) evidence, and state what educational consequences can be expected.

4.1. Proposition One: Exploit the Dual Nature of NG-CPSs

My first proposition is implied by the fact that the paradigm of CPSs fundamentally alters the relationship among humans, technology, and knowledge. Current CPSs are rapidly evolving toward autonomous, intellectualized/intelligent, and socially embedded and personalized configurations. NG-CPSs will be characterized by agentic artificial intelligence, embodied cognition, and deep integration into societal and ecological contexts. They will be not only objects of learning but also enablers of intra-mural (institution-organized) and extra-mural (individual-organized) education[43]. As CPSs acquire planning, reasoning, and adaptive capabilities, they necessarily become active participants in learning processes rather than remaining passive tools. As such, they will fundamentally challenge established educational paradigms. They also become epistemically active systems that participate in decision-making, learning, and adaptation. NG-CPSs will be able to participate in long-term planning, immediate feedback generation, direct and formative assessments, and reflection processes, transforming education from system-centered instruction to human-system co-learning. As distributed systems, they will be able to deal with many learners simultaneously, learn and generalize based on the aggregated experiences, and optimize the learning contents and approaches according to the learners' personal characteristics, plans, and progress. Therefore, education for CPSs must no longer be conceived as the transmission of stable disciplinary knowledge, but as a techno-epistemological synthesis. This paper has argued that the dual role—as both objects and agents of education—constitutes a qualitative shift in educational design and responsibility. Thus, NG-CPSs education must respond to this techno-epistemological transformation concerning how knowledge is produced, integrated, and enacted.

4.2. Proposition Two: Thinking in Knowledge Spaces Leads to Synthesis

Traditional discipline-oriented educational structures are typically reductionist and increasingly misaligned with the integrative nature of CPSs, whose development and operation require the synthesis of heterogeneous knowledge domains, models, and value systems. The basis of NG-CPSs will be post-disciplinary knowledge, which is supposed to be present in proper SOEE. My positioning claim is that CPSs' education must be organized around epistemic integration capacity, rather than driven by disciplinary mastery. This can be provided by knowledge-spaces-oriented thinking. Foundational knowledge for CPSs is not a body of facts but an architecture of integration consisting of (i) systems-oriented engineering epistemologies, (ii) post-disciplinary research and knowledge synthesis practices, (iii) AI as both infrastructure and cognitive partner, and (iv) pedagogical and andragogical models capable of sustaining learning under conditions of complexity and uncertainty. Post-disciplinary SOEE will become possible if the traditional discipline-oriented thinking and disciplinary silos are replaced by mental frameworks oriented to knowledge spaces. The need for it has emerged as a core educational objective of CPSs. The ontological holism of these systems can be experienced without any decomposition, but it cannot be shared and cultivated as knowledge. On the one hand, KSOT facilitates epistemic fluency, which is defined as the ability to navigate, integrate, and critically evaluate diverse sources and forms of knowledge. It is known that it is not possible to step into knowledge synthesis without a forerunning analysis because navigating the parts is a precondition of finding the relations that make knowledge holistic. However, such decomposition does not mean reductionism (i.e., explaining the whole by its parts). Based on KSOT, CPS competence can be defined as the ability to synthesize heterogeneous knowledge, models, and values across domains rather than by depth in isolated disciplines. On the other hand, this reframing does not diminish disciplinary expertise but situates it within broader epistemic architectures oriented toward system paradigms and real-world challenges. I argue that KSOT can (i) replace the current discipline-integration-oriented thinking, important for engineering design and other constructive engineering activities, and (ii) foster synergetic reasoning with knowledge, as happens in the human mind. Efforts have been made to operationalize the concept of knowledge spaces in educational program development and the conceptualization/design of CPSs, but more comprehensive research is needed.

4.3. Proposition Three: Evolving Together with Artificial Intelligence Paradigms

The hottest topic in current SOEE is transformation by generative AI technologies (including the use of large language models in engineering practices). This is, however, not the culmination of the process. Artificial intelligence research will offer innovative technologies that will play an even more pivotal role in the transformation caused by CPSs. Related education must move beyond functional AI literacy to address AI as a form of algorithmic agency and cognitive partnership. My third proposition is that CPSs education must be organized in line with the progression of paradigms of artificial intelligence. Learners must understand not only how AI systems operate, but also how they influence overall behaviour, reasoning processes, and ethical judgments of NG-CPSS. Without this deeper understanding, educational practices risk reinforcing opaque delegation of uncritical reliance on automated decision-making and impact responsibility. Together, these elements define competence as the capacity to design, govern, and ethically steward evolving intellectualized, socialized, personalized, and naturalized NG-CPSs. The evolution from narrow, tool-oriented AI towards adaptive (agentic and embodied) forms of AI fundamentally reshapes cognitive labor, decision authority, and responsibility distribution within CPSs. A current challenge is to understand AI technologies as the algorithmic agency of autonomous systems and to move beyond tool literacy toward creative cognitive partnership. Both educators and learners must understand how AI reshapes possible manifestations, functions, reasoning, behaviour, responsibility, and implications of NG-CPSs. The bottom-line educational implication is that learners must no longer be trained as system developers and operators but as co-evolution designers of living technological ecologies. Implicitly, it assumes the consideration of the different jobs and workplaces that learners may take.

4.4. Proposition Four: Involving Post-Disciplinary Research

A central claim of this paper is that educational innovation cannot come before epistemic innovation. Post-disciplinary education for CPSs relies on post-disciplinary research practices that can integrate perspectives, methodologies, and value frameworks across different domains. I argue that educational synthesis without corresponding epistemic synthesis results in superficial pluri-disciplinarity, a lack of holistic systems thinking, and fragmented understanding. Therefore, transforming CPS education must be based on research cultures that actively go beyond disciplinary boundaries and develop shared epistemic foundations. Looking ahead, seamless and cohesive inclusion of post-disciplinary research and participatory transdisciplinary research is essential in NG-CPSs education. Post-disciplinary education for NG-CPSs is rooted in genuine post-disciplinary research since educational synthesis cannot occur before epistemic synthesis. Beyond just post-disciplinarity, CPSs education should also adopt transdisciplinarity as a necessary approach to address the societal embedding of NG-CPSs. TDEE must manage not only methodological collaboration with non-academic stakeholders but also align worldviews, integrate epistemologies, and assume normative responsibilities. Students need to be prepared to collaborate with diverse actors, negotiate value conflicts, and take responsibility for system-level outcomes. Thus, transdisciplinarity becomes both an epistemic and an ethical practice. A known challenge in NG-CPSs education is that the criteria for what qualifies as proper educational knowledge are partly shaped by non-academic players. Since knowledge constantly evolves, their ongoing engagement is considered an ideal scenario.

4.5. Proposition Five: Involving Civil Stakeholders

While the preceding proposition focuses on the epistemic realization of transdisciplinarity, this proposition positions transdisciplinarity in NG-CPSs education as a dynamic and lasting epistemic, procedural, and normative practice together with civil (societal) stakeholders of various kinds. TDEE is essentially a civilizational learning architecture. It lives or dies depending on how societal stakeholders are structurally involved and contribute to the realization. This emphasizes the necessity of effective involvement and participation approaches. There are several key issues beyond epistemological integration, creative contribution, and shared responsibility regarding the development and conduct of education programs. One of them is the variety of potential stakeholders. Beyond industry partners, representatives of the (i) public sector (city governments, public infrastructure, standards bodies), (ii) civil society (NGOs, labor unions, digital rights groups, user associations), (iii) local communities (residential neighborhoods, user groups, impacted populations), (iv) practitioners (industry startups, system integrators, safety engineers, maintenance technicians), (v) cultural actors (designers, advertisers, artists, media experts, science communicators) may be involved. They need individually tailored approaches and plans, also in terms of keeping commitment and coping with personal changes and varying standpoints. The solution seems to be managing this as a living lab that evolves and adapts to changing resources.

Probably, universal solutions will not be available readily. Elaboration of locally working solutions needs the involvement of stakeholders as early as possible in program development through scenario workshops, future-impact mapping, and value-sensitive innovation exercises. Create formal roles in the taskforce teams, advisory boards, societal impact panels, ethical advisory boards, and community liaison roles to navigate course directions, manage challenges, and maintain long-term partnerships. Bringing in stakeholders as civic educators, practitioner-in-residence, or online mentors, not just guest speakers and reviewers, is a strengthening factor.

4.6. Proposition Six: Necessity of Andragogic Innovation in the Context of NG-CPSs

NG-CPSs education should not only be viewed as a specialized branch, but also as a never-ceasing approach to SOEE. The bottom line is that NG-CPSs education cannot be confined to initial academic training. Due to perpetual conceptual, epistemological, and ecological developments, the pace of technological change, the longevity of CPS deployments, and the evolving nature of societal challenges, it is undeniably necessary to make continuous efforts. The implementation of NG-CPSs education manifests as a dual concern. First, it should be prepared, mastered, and refined by proper strategies in the three stages of institutionalized education. Second, it must extend across the entire lifespan of the professionals or individuals concerned. The largely deterministic nature of the first and the largely indeterministic nature of the second period create tension between them.

The resolution of this tension needs further innovation for NG-CPSs education. It ranges from dedicated pedagogical theories, through andragogical and heutagogical methodologies, to networked AI-enabled virtual learning environments, including NG-CPSs-based education agents. Access to resources may be based on paid services, open-access, or hybrid forms, with possible support from governments. The pedagogical and andragogical strategies must be adapted to the needs of adults, depending on (i) their learning objectives, (ii) proven level of experience, (iii) complexity of the professional competencies, (iv) sophistication of the learning environment, (v) motivation of the learner, and (vi) cultural backgrounds. Lifelong learners need to be aware of educational and professional development models that support them in self-directed learning, imposing reflexivity, contextual adaptation, and continuous competence development under conditions of uncertainty. Successful lifelong learning also needs touchpoints with peers, consultants, experts, and advisors—an issue that involves ensuring availability and organized planning. The elaboration of these mechanisms needs research and development. Presently, it is unclear who the host of lifelong education is or should be. Which institutional, governmental, or regional organizational actors should be involved, and develop alternative frameworks for lifelong learning to support adult learners in self-directed, reflexive, and context-sensitive learning processes after their institutionalized education? Andragogical and heutagogical approaches are therefore not ancillary, but central to sustainable NG-CPSs education.

5. Conclusions

In this section, first, I reflect on the background reasoning and the reported findings and reintegrate the six propositions discussed above. By doing so, I intend to avoid reading the position paper as "here is CPS" → "here is NG-CPS" → "here is creative AI" → "here is education" → "here is future education", and to make the transitional relationships explicit. Obviously and undeniably, there is a strong causal logic beyond what I symbolized above. Instead of the above causality, I attempted to use a different logic in my reasoning and to make it tangible by the following semantic inference scheme: "Because CPSs are becoming X, and AI is proliferating as Y, education must become Z." My intention with this paper was to take a strong epistemological stance: I advocate the need for post-disciplinary knowledge and transdisciplinary synthesis over knowledge spaces in context, to avoid contending disciplines. Because of confusing terminology and the differences in interpretation of concepts, I tried to set up a notional framework (believed to be consistent) based on clear definitions of foundational concepts and their relationships.

I see the central challenge of NG-CPSs education not in technological acceleration, but in the epistemic responsibility under conditions of complexity, uncertainty, and co-evolving intelligence. Taken together, my arguments underscore that the challenge of educating for NG-CPSs is not primarily technological or institutional, but epistemological and organizational. It concerns how knowledge is organized and how responsibility for life-long NG-CPSs education is to be distributed in the age when NG-CPSs become educational agents. Addressing the related challenges requires coordinated innovation in pedagogy, andragogy, research culture, and organizational governance. In conclusion, the education of NG-CPSs must be understood as an ongoing process of epistemic reconfiguration rather than as a daily challenge reduced to curricular adjustment. The central task is not merely to keep pace with technological development, but to cultivate epistemic responsibility, integrative judgment, and adaptive learning capacities in a world of co-evolving human and artificial intelligence. Only through such an approach can CPSs education contribute meaningfully to the design, governance, and stewardship of complex socio-technical systems in the decades to come.

The education of NG-CPSs needs epistemic innovations that include but are not restricted to: (i) a shift from disciplinary knowledge units to knowledge spaces organized around system paradigms, (ii) systems thinking as a foundational epistemology rather than a supplementary skill, and (iii) epistemic fluency as the ability to integrate heterogeneous models, representations, and validation criteria. I argued that holism is not reduced by decomposition in NG-CPSs, because system-level properties such as safety, resilience, trustworthiness, and emergent risk arise from cross-layer couplings that cannot be derived from components in isolation. This is also a reason why a new epistemological framework is needed. On the other hand, holism cannot be operationalized without decomposition in SOEE, because engineering, verification, governance, and operation require bounded models, interfaces, and levels of abstraction. Every NG-CPS is a coupled socio-technical-physical whole. Our decompositions are perspective-bound projections that must be continuously re-integrated and revised in line with their emergent behaviour. Decomposition is therefore a methodological necessity, not an ontological claim about what CPSs ultimately are. It is made challenging by the increasing complexity of NG-CPSs.

Engineering of NG-CPSs is no longer only about building better systems, but about cultivating sustainable, intelligible, and governable human–machine worlds. This requires a shift from interdisciplinary integration to transdisciplinary co-evolution of systems, knowledge, and society. CPSs educators' mental model should be that decomposition of complexities is a methodological necessity rather than an ontological commitment, and holistic CPSs engineering consists in the continuous coordination and revision of partial representations in relation to the coupled whole. The paper by Horváth and Abou Eddahab-Burke[44] provides an example of treating decomposition as a means of coping with complexity, rather than explaining what reality is. Practicing educators may experience how the role of reductionism has changed—from being the goal of knowledge handling to being a means within an integrative, problem-centered post-disciplinary education practice. Likewise, the role of analysis has been changed from 'serving as a foundation' to 'enabling within ongoing synthesis'.

Some limitations must be mentioned. The pedagogical goal of this paper was to close the conceptual loop from the paradigm of CPSs, through the prognostics of NG-CPSs and the principles of PDEE/TDEE, to necessary pedagogical and andragogical innovations. The background research was challenged by the exceptional conceptual breadth that is associated with CPSs, NG-CPSs, SOEE, and continuing learning. This was also present during the elaboration. The large reasoning loop presented in this paper is difficult to cover empirically. This explains why the form of a position paper, written in full academic prose, has been preferred. This made it possible to go beyond a coherent but decisively ending research or review paper or a summarizing essay. To help readers come away with an understanding of my exact position on the various hot topics, the major proposals are formulated as propositions. As the paper of León and Lipuma[45] argued, even interdisciplinary and classical transdisciplinary modes are insufficient under extreme complexity and rapid changes. This is why they proposed a cyber-transdisciplinary epistemic mode, where GAI systems are co-agents in knowledge production—not just tools, but participants in the synthesis and governance of knowledge. The novel concept of cyber-transdisciplinarity foregrounds co-agency with AI, which opens new epistemic and governance territories beyond human-only synthesis. However, a deeper understanding and operationalization of it without a loss of epistemic rigor and with ethical opacity needs foundational research in the coming years. In the current situation, an extensive research agenda and roadmap development is suggested, instead of trendy topics and approaches.

In the context of post-disciplinary and transdisciplinary NG-CPSs, it is of the highest importance to establish a general-enough methodics for autonomous and lifelong learning to fully "close the loop". There are many sources of tensions and risks in NG-CPSs education, such as (i) loss of disciplinary depth, (ii) over-automation of cognition, (iii) challenge of coping with epistemological complexity, and (iv) ethical dilution via tool-centric education. Post-disciplinary education should adopt a dynamic integration loop in its epistemological and engineering routine. In practice, it means a recursive loop including (i) adopting a holistic view of the coupled system and its environment, (ii) introducing decompositions into components, layers, models, and perspectives for tractability, (iii) analyzing, designing, and verifying within these partial representations, (iv) re-integrating results at the system level through simulation, testing, monitoring, and governance, and (v) revising the decompositions in response to emergent behaviour and boundary-crossing effects. This loop reflects that CPSs are not merely assembled systems, but evolving socio-technical-physical processes. My position and closing stance are that the central challenge is not whether education can keep up with NG-CPSs, but whether it can retain epistemic responsibility while doing so.

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AI Use Statement

In the exploration phase of the research, Google Scholar with AI Mode was used to find published articles and documents related to the listed keywords and/or professional terms/phrases that have been included in the section and subsection headings. In the finalization phase, the public version of Grammarly was used for grammatical and style enhancement. No specific 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.

Abbreviations

AI: artificial intelligence
AIDM: additional interest-driven module
CCDM: compulsory cross-disciplinary module
CCPSH: cognitive–cyber–physical–social–human
CDIO: conceive–design–implement–operate
CMDM: compulsory mono-disciplinary module
CPSs: cyber-physical systems
CPDM: compulsory post-disciplinary module
CRM: content relationship map
CTDM: compulsory transdisciplinary module
DOI: digital object identifier
EAI: embodied artificial intelligence
ECDM: elective cross-disciplinary module
ECPSs: educational cyber-physical systems
EMDM: elective mono-disciplinary module
EPCW: educational program content warehouse
ETDM: elective transdisciplinary module
FTFC: face-to-face course
GenAI: generative artificial intelligence
KSOT: knowledge-spaces-oriented thinking
MOOCs: massive open online courses
NG-CPSs: next-generation cyber-physical systems
PAI: physical artificial intelligence
PDEE: post-disciplinary engineering education
POEE: processes-oriented engineering education
SOEE: systems-oriented engineering education
PSFs: paradigmatic system features
TDEE: transdisciplinary engineering education

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