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Framing Supradisciplinary Research for Intellectualized Cyber-Physical Systems: An Unfinished Story

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Conceptualization and design of intellectualized, socialized, and personalized cyber-physical systems (CPSs) need integration of existing knowledge across the involved disciplines, as well as exploration and synthesis of novel knowledge beyond disciplinary boundaries. The latter needs a combined use of interdisciplinary, multidisciplinary, and transdisciplinary research. Supradisciplinary research has emerged as a new doctrine of combining these research approaches from epistemological, methodological, and procedural perspectives. However, no methodology can be found in the literature that could facilitate the practical execution of supradisciplinary research programs. This position paper proposes a conceptual framework that can be used as a blueprint for operationalization of such undertakings. The framework rests on six generic pillars: (i) problematics, (ii) infrastructure, (iii) method, (iv) stakeholders, (v) operations, and (vi) knowledge. It specifies the major concerns that have to be taken into consideration in a systematic manner in developing executional scenarios for supradisciplinary research. The framework facilitates (i) management of research organization tasks, (ii) joint formation of shared research infrastructure, (ii) setting up concrete research program, (iii) academic partnering and public stakeholder involvement, (iv) process flow management and capacity/competence allocation, (v) a holistic knowledge synthesis, assessment, and consolidation, and (vi) development of tools supporting the preparation and execution of large-scale supradisciplinary research. In its current form, it does not cover the specific societal and personal issues of a successful organization of the inquiry at individual researchers, research teams, and research community levels. A community-based follow-up research may focus on the practical application and testing of the framework in concrete cases—a task that an individual researcher cannot address. [DOI: 10.1115/1.4062327]

Keywords: cyber-physical system design and operation, knowledge engineering

1 Diversification of Cyber-Physical Systems

Currently, cyber-physical systems (CPSs) research is one of the most flourishing fields of academic and industrial interests. Scientific convergence and technological integration have been creating a basis for realizing new cyber-physical system concepts not only for industrial applications but also for non-industrial ones [1]. Traditionally, CPSs have been defined as confluences of the knowledge and technologies of computing and informing, and the knowledge and technologies of physical artifacts and engineered systems toward situated, intelligent operation and servicing as actors in human and social contexts [2]. The concepts and technologies of wireless sensor networks, the Internet of Things, and edge computing establish an infrastructural platform which is included in most of the industrial CPSs [3]. However, it does not play any crucial role in application-specific problem-solving by these systems. The latter is supported by the intellectualization (cognitive design and engineering) of CPSs. This goes together hand-in-hand with the present hype of artificial intelligence research and computational intelligence development.

In many often-cited publications, CPSs are alternatively interpreted as (i) functionally and technologically extended embedded systems, (ii) augmented Internet of Things systems, (iii) collaborative advanced mechatronics systems, or (iv) agent/actor-based adaptive systems. Together with many scholars, the author regards intellectualized CPSs (i*CPSs) as a direct outcome of scientific convergence and technology integration. These are getting momentum, and on the one hand, they are blending systems science with biological science, cognitive science, behavioral science, and social science, and on the other hand, they are integrating electromechanical technology, computing technology, information technology, knowledge technology, nanotechnology, biotechnology, and human technology. The technological convergence is culminating in a new phenomenon which is often referred to as the bits–atoms–neurons–genes–memes (BANGM) revolution [4]. This revolution is fueled by the presently unexplored or only partially known possibilities of fusing bits, atoms, neurons,

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genes, and memes in various systems (Fig. 1). It is conceived that this will lead to a supradisciplinary systems and technologies science.

Conventional CPSs are practical examples of the interconnection of bits and atoms, while intellectualized CPSs represent integration of knowledge with bits and atoms in human and social contexts [5]. Likewise, amalgamation of neurons and genes in various industrial and non-industrial systems contributes to sophisticated implementations of system intelligence, and inclusion memes in systems may forward them toward socialized and personalized behavior. The integration of neurons has lent itself to the emergence of cyber-biophysical systems (represented by assistive and corrective implants and artificial limbs/augmentations). The cyber-world is gradually penetrating the unanimated and animated natural worlds through various synergistic technologies. As a consequence, i*CPSs can contribute to extending human capabilities in the perceptual and cognitive domains in addition to the physical and motor domains. Altogether, these advances result in a massive diversification of i*CPSs.

System intellect is the total of all perceptive, cognitive, and motor abilities and powers of an engineered system for controlled physical changes, context-dependent reasoning, formal decision-making, rational problem-solving, and purposeful adaptation toward its optimum operational state and performance, based on human-provided or self-acquired physical resources and computational mechanisms. In practice, system intellect is implemented based on processing problem-solving knowledge by ampliative computational mechanisms in some application contexts. System intellectualization is the complex process of seeking intellectual character for engineered systems in an application-specific manner and through the implementation of synthetic intellect as their complex, rational, and practical problem-solving power and capacity, with partial or full ignorance of the reproduction of human-like consciousness and other characteristics of emotional or psychological significance. The use of the term "intellectualized engineering systems" allows us to differentiate systems that are developed for solving complex application problems (for instance, autonomous transportation systems, personalized home-care systems, or precision agricultural systems) from those systems that are developed to mimic various manifestations of human intelligence, such as artificial vision, speech recognition, and machine learning. Furthermore, using the word "intellectualized" helps avoid the conceptual confusion that has been introduced by the terms "intelligent systems" and "intelligent cyber-physical systems," respectively.

Reflected by the current literature, three trends of diversification of CPSs can be recognized. These are termed (i) intellectual diversification, (ii) application diversification, and (iii) disciplinary diversification (Fig. 2). Intellectual diversification is happening due to the perpetual increase of cognitive capabilities of systems [6]. Current second-generation CPSs offer smart behavior based on their dynamic situation assessing and self-adaptation capabilities, whereas third-generation CPSs will be characterized by some level of cognizance of the probable and possible objectives and performances, and will enhance themselves by self-evolution. Application diversification simply means that CPSs have a growing range of functionalities, and based on these, they are able to provide dedicated functional services for more and more application domains and penetrate real-life processes in these domains. Strongly application-orientated CPSs are typically distinguished by the acronym X-CPSs where X stands for the name (or only the first letter of the name) of the application field. Disciplinary diversification is associated with the variety of foundational knowledge and disciplinary resources that are used for the implementation of various cyber-physical systems. As mentioned earlier, bodies of knowledge of social, human, biological, nano, etc., and disciplinary domains are considered in their conceptualization and design to make them suitable to tackle problems that could not be handled otherwise. Systems embodying such disciplinary bodies of knowledge are referred to as CPX systems, where X stands for the name of the discipline, for instance, cyber-physical–social and cyber-physical-cognitive systems.

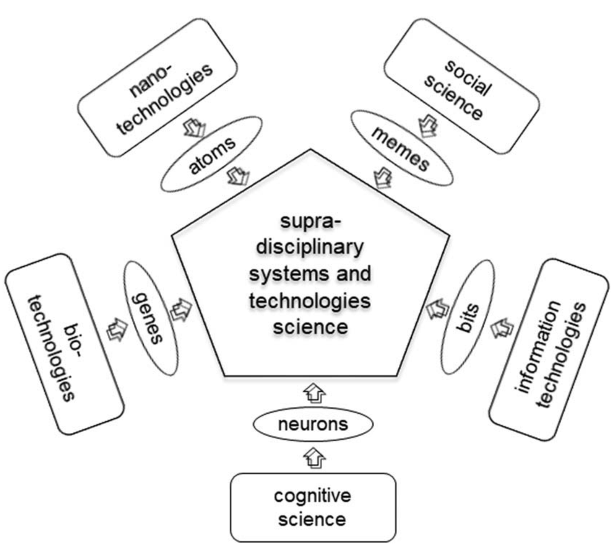

Fig. 1 Convergence of engineering technologies

2 Emerging Problematics of Early-Stage Collective Research for Cyber-Physical Systems

The above-described multi-dimensional diversification of cyber-physical systems raises many new challenges to cope with. In addition to the already known challenges (such as aggregative complexity, technological heterogeneity, functional dependence, stakeholder involvement, operational resilience, and safety and security), a partly research methodological and partly engineering epistemological challenge is also raised [7]. There are two sources of this latter challenge. The first one is the need to explore and synthesize proper cross-disciplinary (holistic) knowledge for conceptualization, design, and engineering of novel cyber-physical systems [8]. The second one is in the traditional reductionist culture of system development that separates the tasks of system development and allocates them to distinct departments [9]. These two phenomena eventually boil down to the need for collective research and feeding the development process with synthesized disciplinary knowledge. In turn, this gives the floor to the above-mentioned research methodological and engineering epistemological challenge [10]. The two main questions are: How to conduct postdisciplinary research in the early stages of CPSs development? and How to synthesize the knowledge during the research process toward the most reliable and useful shared intellect?

The main conjecture (and working hypothesis) of the research underpinning this position paper has been that a pluridisciplinary or postdisciplinary research approach may fulfill the requirement. These inquiry approaches require two or more disciplines to combine their knowledge, methods, and expertise to jointly explore, confirm, and deliver research outcomes (e.g., theories, laws, facts) appropriate for a common subject area. The remaining part of the paper argues that, in line with the multi-dimensional diversification of cyber-physical systems, a supradisciplinary research approach is indeed needed to explore and scrutinize knowledge for their development in the conceptualization and design stages. Though the concept of supradisciplinary research is known and addressed in the related literature, apart from the general methodological dispositions, no specific conceptual frameworks, framing methodologies, or process scenarios have been presented, particularly not in the context of research activities and knowledge demands in the early developmental stages of intellectualized, socialized, and personalized cyber-physical systems [11]. The author interprets it as a "problematics" in itself, which involves

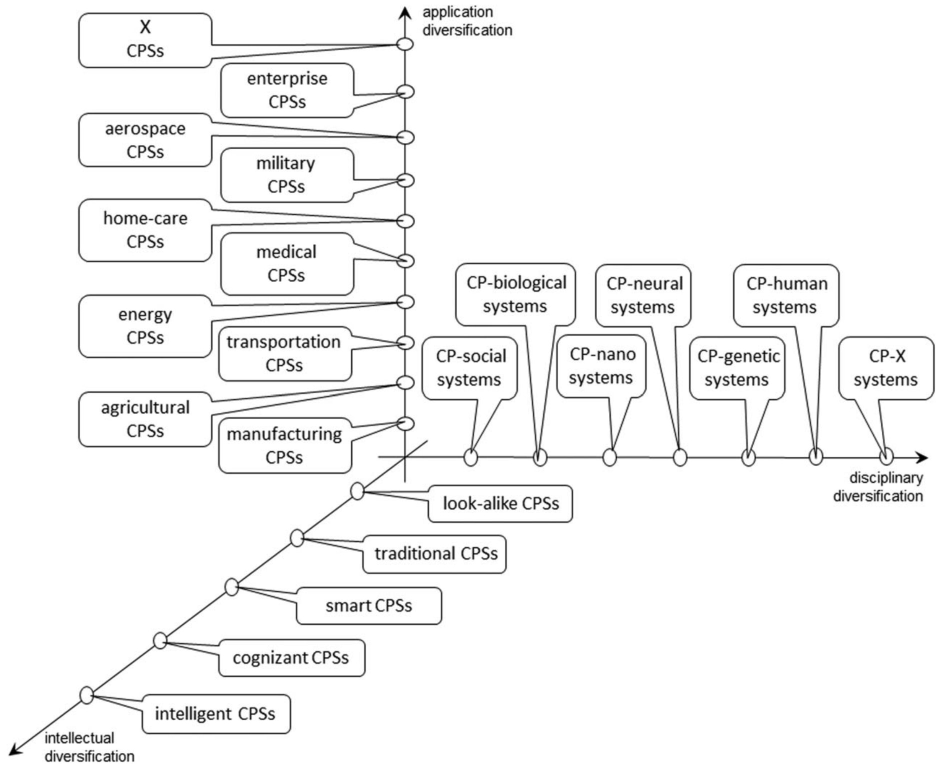

Fig. 2 Dimensions of diversification of cyber-physical systems

intertwined scientific, technological, procedural, social, human, and business aspects.

The current literature is scarce on publications that would explain this "problematics" and would offer a receipt for dealing with it. As posited in Ref. [1], the science of cyber-physical systems is still in the stage of formation and the methodologies of doing pluridisciplinary research in this field have yet not reached further than their embryonic stage. Concerning the development of comprehensive multidisciplinary or transdisciplinary theories, only a few efforts have been reported in the contemporary literature [12]. Therefore, based on a synthesis of the outcomes of his previous research work, a multi-focal literature survey and expert interrogations, critical systems thinking, and philosophical and methodological speculations, as well as on retroductive reasoning [13], the author proposes a generic framework for conducting supradisciplinary research in multi-dimensionally diversified CPSs. The importance of this work and the proposed framework lies in the foreseen even more intense diversification of the next generation of CPSs. The next section analyses the methodological convergence of the various research approaches. Afterward, the main tenets of team science are discussed, and the different forms of research coworking are presented. The last part of the paper presents the six domains of concern and the blueprint of the proposed framework.

3 Convergence of Individual and Collective Research Approaches

The twenty-first-century science is concurrently driven by transdisciplinary convergence, structural reorganization, and social transformation [14]. The fact of the matter is that both convergence and divergence are perpetually present and interoperate in science, knowledge, and technology. Consequently, new competing research philosophies and strategies are emerging that have not been consolidated yet. The last decades have seen the transition from the so-called Mode 1 science to Mode 2 science [15]. The former is the old paradigm of scientific inquiry and (i) is characterized by the hegemony of theoretical and experimental discoveries, (ii) establishes an internally-driven taxonomy of branches and disciplines of science, and (iii) acknowledges the autonomy of individual scientists and their host institutions. It is characterized by an analytical thinking approach that has its roots in reductionism [16]. The latter (i) is a new paradigm of socially distributed knowledge production, (ii) has a pluridisciplinary, collaborative, and application-oriented nature, (iii) is the subject of multiple accountabilities, and (iv) is typically considered in technological, social, political, and economic contexts. Analytic and prognostic systems thinking plays an important role in practicing Mode 2 science. Systems thinking (i) explains the manifestation and behavior of systems as a whole, (ii) is dominated by abstraction and synthesis, and (iii) studies emerging and relational properties. It is supposed to be extended to the human behavioral domains (cognition, communication, leadership, etc.) [17]. As a consequence of these, systems thinking increases all forms of complexity and heterogeneity, but facilitates addressing the sustainability of the environment, economy, and society. The overview of the latest theoretical and methodological developments in scientific research also needs (critical) systems thinking [18].

It is known that the terms interdisciplinary, multidisciplinary, and transdisciplinary are ambiguously defined and interchangeably used in the literature. Therefore, it seems to be useful to elaborate on the interpretation and use of these terms in this part of the paper. With this in mind, a comprehensive landscape of generic research approaches is shown in Fig. 3. As an overall trend, the move from an individual-focused unidisciplinary research approach, through pluridisciplinary ones, toward postdisciplinary approaches has been identified [19]. In practice, it means that pluridisciplinary programs are also conducted in addition to monodisciplinary research programs. A research approach is "multiple disciplinary" if more than one discipline is involved, but the nature of their involvement is unknown or unspecified. As a common term, pluridisciplinary refers to research that may involve interdisciplinary, multidisciplinary, and transdisciplinary research programs and approaches [20,21]. While monodisciplinary research inquiries are conducted from the perspective of a single discipline, pluridisciplinary programs make attempts to investigate phenomena and

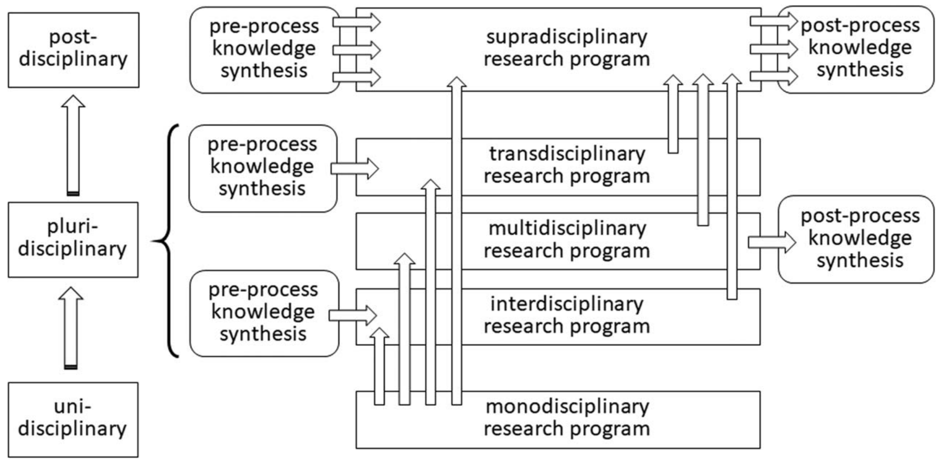

Fig. 3 Overview of the generic research approaches

problematics from multiple perspectives in an integrated manner. Supradisciplinarity is the descriptor of the doctrine of hybridization between knowledge domains. It means conducting monodisciplinary, interdisciplinary, multidisciplinary, and transdisciplinary research programs or activities simultaneously and purposefully in concert. While monodisciplinary research can be best characterized by the word "distributed," a single-word descriptor for interdisciplinary research is "interactive," for multidisciplinary is "additive," and for transdisciplinary is "holistic." As a recently conceptualized realization of a postdisciplinary philosophy, supradisciplinary research can be depicted as a "combinatorial" approach.

Individual investigators orientated unidisciplinary approach is a historical development. It counts on the insights and talents of individual researchers, working independently or in groups. Typically, doctoral (promotion) research regulations and frameworks still strictly follow the ideal of unidisciplinary, single-investigator research approaches. Notwithstanding, due to the institutionalization of scientific research, it has been scaled up to large monodisciplinary projects based on team formation and collaboration. Though it is often deemed as exhausted from a praxiological perspective, it remains an indispensable kernel of doing scientific research. Neither modern pluridisciplinary nor postdisciplinary (or meta-disciplinary) research philosophies are against this.

Interdisciplinarity assumes creating links between disciplines and a coordinated inquiry approach, including the establishment of a shared knowledge and method platform at launching projects (front-end integration) [22]. Interdisciplinarity is a subject of philosophical argumentation [23]. Interdisciplinary research addresses phenomena that are not directly and completely covered by the concerned disciplines [24]. It assumes close interaction in coworking and assumes the agreement of the investigators from different disciplines on the objectives and the different analysis and synthesis methods [25]. An interdisciplinary research approach involves the interaction and coordination between more than one discipline, aiming at (i) development of knowledge in each of the concerned disciplines, (ii) transferring knowledge from one discipline to another, and (iii) transforming knowledge of one discipline under the influence of another discipline [26]. These assume collaboration and the emergence of a new thought style [27].

Multidisciplinarity draws on knowledge from different disciplines, but stays within its boundaries [28]. Multidisciplinary research projects are carried out independently by unidisciplinary researchers, but they are informed about the work of the other disciplines throughout the process. New knowledge is learned through the individual interest windows of the included disciplines, and evaluated and combined in the conclusive stage of research projects. In other words, the novel knowledge is synthesized and consolidated at the end of the conducted projects (back-end integration). No specific execution methodologies have been publicized for this purpose. Multidisciplinary research collaboration involves (i) collective determination of the goals, (ii) working out a strategy/approach to achieving the goals, (iii) sharing physical, intellectual, and intangible resources, and (iv) building common grounds and consensus. Multidisciplinary research teams are supposed to produce (i) a coherent picture of the subject matter of the scientific study, (ii) a description/explanation of (parts of) the problematics or phenomenon, and (iii) a set of ranked theories to underpin potential theories or solutions.

Transdisciplinarity integrates natural, social, and technical sciences in a social context and transcends their traditional boundaries [29]. Transdisciplinarity also signifies lively interactions between stakeholders and crossing the boundaries between scientific and non-scientific communities (representatives of industry, government, and/or civil organizations) with the goal of reaching out to the entire society [30]. Practicing transdisciplinarity is usually a challenging task because it needs an epistemological and organizational framework [31]. Transdisciplinary research is a blending of interdisciplinary perspectives to produce a hybrid perspective of two or more disciplines [32]. Researchers from different backgrounds have to find each other, get acquainted, and derive a common motivation [33]. They should form linked research teams and research communities. Successful research conduct assumes an explicit specification of the goals as well as a widely-based knowledge and process synthesis (front-end integration) [34]. That is, before the start of their collaborative work, they have to synthesize a common platform of shared knowledge [35]. This knowledge is subject to new types of quality control and extra-scientific social criteria, including public reviews [36]. The researchers, who are coworking in teams and communities, must learn to understand and appreciate each other's perspectives, forerunning work, and new results. They should work out procedural and administrative scenarios for long-term cooperation or coadunation. Without these, they cannot reap the extra benefits of collaborating across disciplinary boundaries [37]. Working in a transformative manner has also been identified as a paradigmatic characteristic of transdisciplinary research programs and projects [38].

A supradisciplinary research approach also involves more than one discipline as well as all of the previously mentioned research approaches. It assumes that the nature and essence of their involvement is designed, planned, and specified before launching any program or project. Supradisciplinary research is deemed a conceptually and empirically grounded constitutional element of Mode 2 knowledge production or simply as if it was the same thing as Mode 2 science. Supradisciplinary research has ontological, epistemological, methodological, and praxiological conditions. The ontological condition is that its paradigm is accepted as trustful and realistic. The epistemological condition is that a preliminary knowledge synthesis [39], as well as an unbiased synthesis of the novel findings, is possible [40]. The methodological condition is that a conceptual framework/platform can be created together with a pool of complementary research methods. The praxiological condition is about overstepping the (research) cultural boundaries by a holistic relational process, in which knowledge is produced through transactions of stakeholders and supporting communal project management [41]. The knowledge created by supradisciplinary research is consequently understood to be: (i) reflexive with regard to social accountability, (ii) traceable back to its starting point in societal needs, and (iii) servicing its social "stakeholders" and applied research. In other words, it offers a genre of knowledge that manifests in the contexts of applications and, therefore, cannot be classified according to a distinction between scientific branches.

4 Team Science to Assist Mode 2 Science

According to a widely accepted definition, team science is a collaborative effort to address a scientific challenge that leverages the strengths and expertise of professionals trained in different fields [42]. Team science is one of the sets of strategies and efforts that advance convergence [43]. It utilizes the core principles and best practices of community psychology to enable the current transformation in science and to develop research competencies for groups and communities. One of the main objectives is to develop general principles and trustworthy effective practices for both co-located and dislocated (online) coworking [44]. Team science is not against the traditional single-investigator-driven research approaches, but wants to learn from their limitations and augment them toward group- and community-oriented research approaches. It studies how coordinated teams of diverse skills and knowledge can tackle complex scientific and societal problems and emergent issues [45]. It promotes both intra-personal competencies (attitudes, knowledge, skill, and experiences) and interpersonal competencies (socialization, communication, empathy, and trust). Team science also studies elements of team and community processes (common vision, communal mission, tactical goals, shared understanding, and responsible roles) and institutional infrastructure and policies (hiring, promotion, experiences, desires, interdependence, organization, funding opportunities, data management, networking, and road mapping) [46]. Furthermore, it studies the broader influences of coworking (e.g., history, cooperation framework, publishing forums, academic events, and industrial relations) [47].

Undertaking research in a collaborative way is called upon by convergence. Team science intends a generic theory to explain multi-scale collaboration in a level- and context-independent manner [48]. The primary conjecture is that a research team- or community-based approach is the proper organizational form and one key strategy for tackling complex problems across boundaries. However, it is challenged by the difficulties of establishing partnerships across multiple local and international institutions. It remains a task for top management of these institutions to recognize, institutionalize, and operationalize team science. They have to think of both horizontal integration (bringing together disciplines that share common features, methodological approaches, and overlapping background knowledge) and vertical integration (linking disciplines across multiple types and levels of analysis and synthesis). Insights from the social and behavioral sciences help form and sustain effective research teams and communities. In addition, bridging across interrelated research interest areas is also supported by international personal networks and individual investigators, who have broad expertise in more than one area and embody the idea of convergence.

Convergence transcends disciplinary boundaries, even extending beyond what is traditionally regarded as science. Reportedly, (i) raising public/professional awareness of convergence, (ii) building common grounds and consensus, and (iii) establishing scientific cultures that support convergence are catalysts of new scientific knowledge and applications. Formation of integration (from incidental partnership to strategic alliance) is a non-deterministic, interest-driven process. In current practice, integration of collective work is usually emergent and volatile, driven by project calls and the interest of funders. Theories of team science should be more articulated with regard to the various practical manifestations of collective work, which can be (i) cooperation (involving information sharing and supporting organizational research outcomes), (ii) coordination (harmonizing research activities and support of mutual benefits), (iii) collaboration (giving up some degree of research independence in an effort to realize a shared goal), and (iv) coadunation (achieving the state or condition of being united by gradual synergy forming and growth in research; Fig. 4). Theories must also explain the time-dependence of the drivers (e.g., temporal changes in complex societal needs, advancement of technologies, novel business models, diversification of knowledge, and time-influenced organizational principles.) and the obstacles of coworking (e.g., culture of coping alone, attitudinal disinterest, IP protectionism, insufficient competencies, and fear of transparency).

Scientific research has been heavily institutionalized over the last century and is typically conducted in a hierarchical organization. Its structural reorganization proceeds according to the concept of organizational heterarchy that establishes interdependence, even independence, and relationships of the stakeholders of research. In addition to extensive academic research collaboration, addressing complex societal challenges also needs collaboration with various public stakeholders [49]. The paradigmatic model has been multi-institutional project-based research collaboration in cooperating teams. In such projects, collective competence and wisdom have been deemed more essential than individual ingenuity and diligence. Typically experienced in research cooperation over geographic, economic, and cultural boundaries, the term cultural diversity has been used widely to refer to the differences of humans/societies in a specific region. It is reflected in the mental models and behavioral styles and results in different value systems. Cultural diversity in research is difficult to deal with because reasoning, decision-making, behavioral, and interaction models are all involved. The literature also informs us about the fact that many multi-national collaborative research projects suffered from "research cultural clashes" in the lack of common ground, building awareness, showing openness, and exercising patience.

In addition to large-scale naturally existing or artificially created phenomena, societal problematics is also gaining importance. The term problematics is used to refer to the abstraction of multiple, holistically evolving practical challenges (inherently related wicked problems) that are uncertain or not settled, complicated to handle and solve, difficult to decide upon, and their future state is open to debate [50]. Problematics constitutes complex, heterogeneous, multi-faceted research challenges in a general context, such as the problematics of artificial intelligence or sustainable living [51]. Many researchers see societal problematics as a specific form of observable phenomena (a set of interrelated wicked scientific problems of the same nature) whose study (description, explanation, and regulation) needs collective and holistic research efforts and often multi-level simulations based on computational modeling. Exemplified by multi-factorial challenges such as climate change, energy provisioning, circular production, extreme social stratification, ecological sustainability, informational smog, well-being, pandemics and chronic diseases, profitable recycling, sociotechnological problematics cannot be reduced to component problems due to their innate holism.

5 Related Organizational, Management, and Social Issues

Pluridisciplinary research approaches consider some observable problematics (or phenomenon) from different disciplinary viewpoints and intend to neatly merge and integrate relevant parts

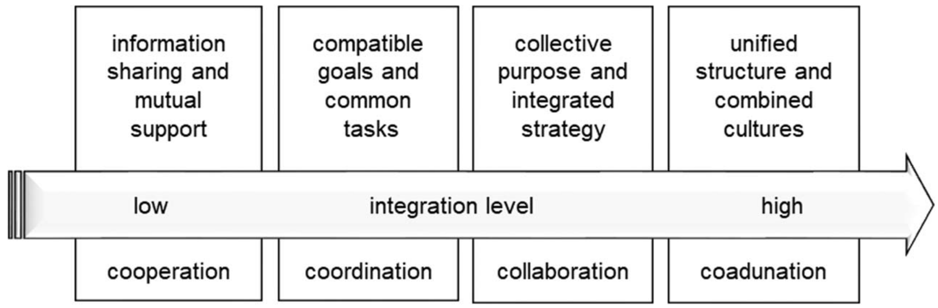

Fig. 4 Forms of coworking in pluridisciplinary research

(concepts, models, methods, and findings) of different scientific disciplines in systematic inquiries [52]. These approaches require understanding the previous research and perspectives of the others with whom they intend to work and go together with a confrontation of the scientific concepts, models, methods, and findings of the concerned disciplines. They are epistemologically and socially constructivist approaches that highlight the emergent, recursive, and communal nature of knowledge production. The various approaches have different positions with regard to integration, and attempts have been made to develop formal composition methodologies and methods for fusing harmonizing theories [53]. They advocate that much knowledge emerges through academic interaction during the research process and through social action itself and recognize informal social and cultural integration mechanisms as essential. The need for synthesizing and sharing knowledge is present and important during the early negotiation phases of research projects in order to build up the required redundancy, as well as at the conclusion phases of research projects in order to consolidate the new knowledge [54].

The establishment process of supradisciplinary research programs and projects offers opportunities for addressing social issues and enhancing the social skills of the involved researchers representing multiple disciplinary domains. The specific goals of social management are visualized in Fig. 5. This model considers six stages of academic and public socialization of research [55]. The goal in the first stage is to learn and interlink the subject knowledge, methodological know-how, and working culture of the researchers representing the involved competence domains. The goal of the second stage is sharing mental models and conceptual frames, whereas the goal of the third stage is exchanging interdisciplinary synthetic skills and experiences. These two processes contribute to the development of collaborative social skills. The specific goals of the fourth stage are to establish a hybrid virtual knowledge base and a virtual method warehouse, with the intention of helping the involved individual researchers and research teams to familiarize themselves with the bodies of knowledge and the arsenal of methods, tools, and instruments used by others. Together with activities in the two preceding stages, this creates a so-called professional reference space for all researchers and teams. In the fifth stage, a joint problematics space is created and maintained. This makes it possible for the involved researchers to address the same problematics, while they look at and interpret them from their own perspectives. As an outcome, epistemic translations take place which offer deeper insights and blur the boundaries if they still exist in the professional reference space. The last stage is the actual organization and management of supradisciplinary research programs and projects, which is facilitated by growing social awareness and managerial competencies.

Pluridisciplinary research approaches direct attention to dimensions such as research management, partnership, sharing,

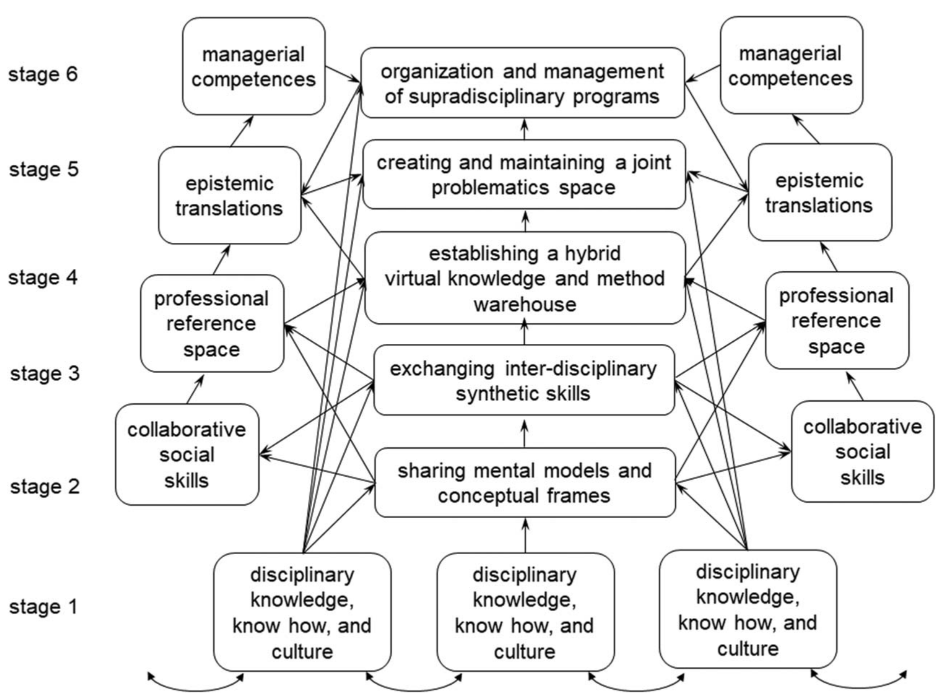

Fig. 5 Creating joint intellectual spaces

productivity, and exploitation [56]. Actually, they place the layers of organization, management, and utilization above the layers of competence development, execution of inquiry, and dissemination of the results. Successful program/project management also assumes exposing academic leadership. In general, research leaders should (i) address the barriers to effective professional and social convergence, and strong partnerships within and across institutions, (ii) develop policies, guidelines, and practices to support and evaluate convergent research, (iii) utilize the expertise of economic, social, and behavioral sciences to realize best practices, (iv) master program management and strategic planning when forming a research initiative, (v) be aware of the most effective recruitment practices, research support policies, risk analysis, and recovery models, cost and revenue allocation models, including catalytic seed funding's, and (vi) apply comparative evaluation policies, tenure and promotion advancement, and unique evaluation criteria for rewarding both professional and social achievements.

6 Domain of Concerns and a Blueprint of the Proposed Framework

Organization of problematics-driven design research for the development of next-generation CPSs is a new challenge. Due to its complexity, it can be addressed only by a supradisciplinary research approach that enables collective knowledge exploration and integration processes. As discussed in the preceding sections, such an approach is influenced by a large number of factors. Of paramount importance are: (i) the organization theory of holistic co-processes, (ii) the principles and recommendations of team science, (iii) the praxiological issues of twenty-first-century (Mode 2) science, (iv) the societal epistemology of emerging problematics, and the (v) psychologic theory of creative communities (Fig. 6).

Operationalization of a supradisciplinary research approach needs a conceptual framework, which is supposed to specify both the ontological pillars and the methodological–procedural concerns. Based on what has been discussed in the preceding sections of the paper, six ontological pillars have been identified, namely (i) the investigated complex problematics (or phenomena), (ii) the integrated and shared research infrastructure, (iii) the applied research methodics, (iv) the involved academic and public stakeholders, (v) the establishment and execution inquiry operations, and (vi) the input and output knowledge. As shown in Fig. 7, these ontological pillars of supradisciplinary research are actually strongly interlinked, even intertwined.

In simple words, the main requirement concerning the conceptual framework is to explain what the associated concerns are and in

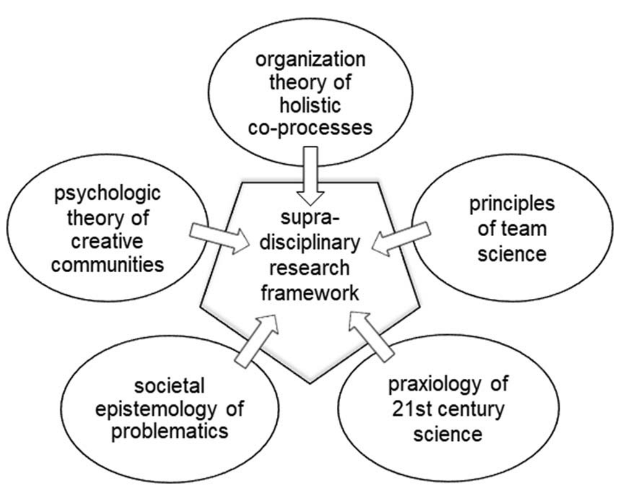

Fig. 6 Main factors influencing a framework of supradisciplinary research

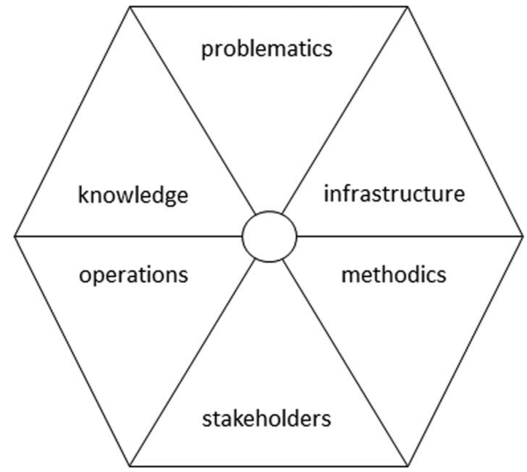

Fig. 7 The six pillars of implementation of supradisciplinary research

which order they should be taken into consideration at organizing supradisciplinary research [57]. As the upright pillars supporting a building are made up of bricks, the ontological pillars of the framework are built from conceptual building blocks. In fact, these building blocks are concerns of realization. This means that the structure of the conceptual framework has been defined by the ontological pillars, whereas its specific content has been compiled from the related concerns of realization.

The blueprint of the conceptual framework is shown in Fig. 8. Based on their intertwined nature, no ordering logic can be imposed on the ontological pillars. On the other hand, the order of the blocks of the pillars shows a procedural order. For instance, handling the problematics commences with exploring the space of relevant complex problematics (or phenomena) and finding the most appropriate one (first choice) for common research interest and concludes with planning and starting the exploitation of the novel intellectual assets. The establishment of a shared research infrastructure starts with the overview of the existing research facilities and the planning of the additionally needed facilities towards a functional integration of laboratories and finishes with designing and provisioning security and safety services. The elaboration of the research methods (designing the inquiry processes, defining sets of research methods and instruments, and stating the applicability and performance criteria, without a common underpinning theory) starts with a research task analysis and concludes with coherence and correspondence analysis of the outcome theories. The stakeholder integration starts with partnering strategy development, involving both academic and public stakeholders, and concludes with the enhancement of synthetic professional and social skills. The establishment and execution of inquiry operations start with the elaboration of the principles of efficient inquiries and operative leadership and extend to the management of progress reporting and reviews. The engineering and management of input and output knowledge commence with studying the past activities and background knowledge of the partners and concludes with the internal and external consolidation of the new knowledge. In practice, working on the six ordered groups of concerns happens concurrently and interdependently.

The proposed framework advises on how to organize and execute supradisciplinary research, but it does actually not describe what to study. Therefore, it should be seen as a kind of meta-research design that has to be combined with specific research models that are foreseen results of addressing the dedicated concerns in the thread of methods. The research models can convey information about complex problematics or phenomena that have significance and do indeed need supradisciplinary research approach, including team- and community-based inquiry efforts. In the context of

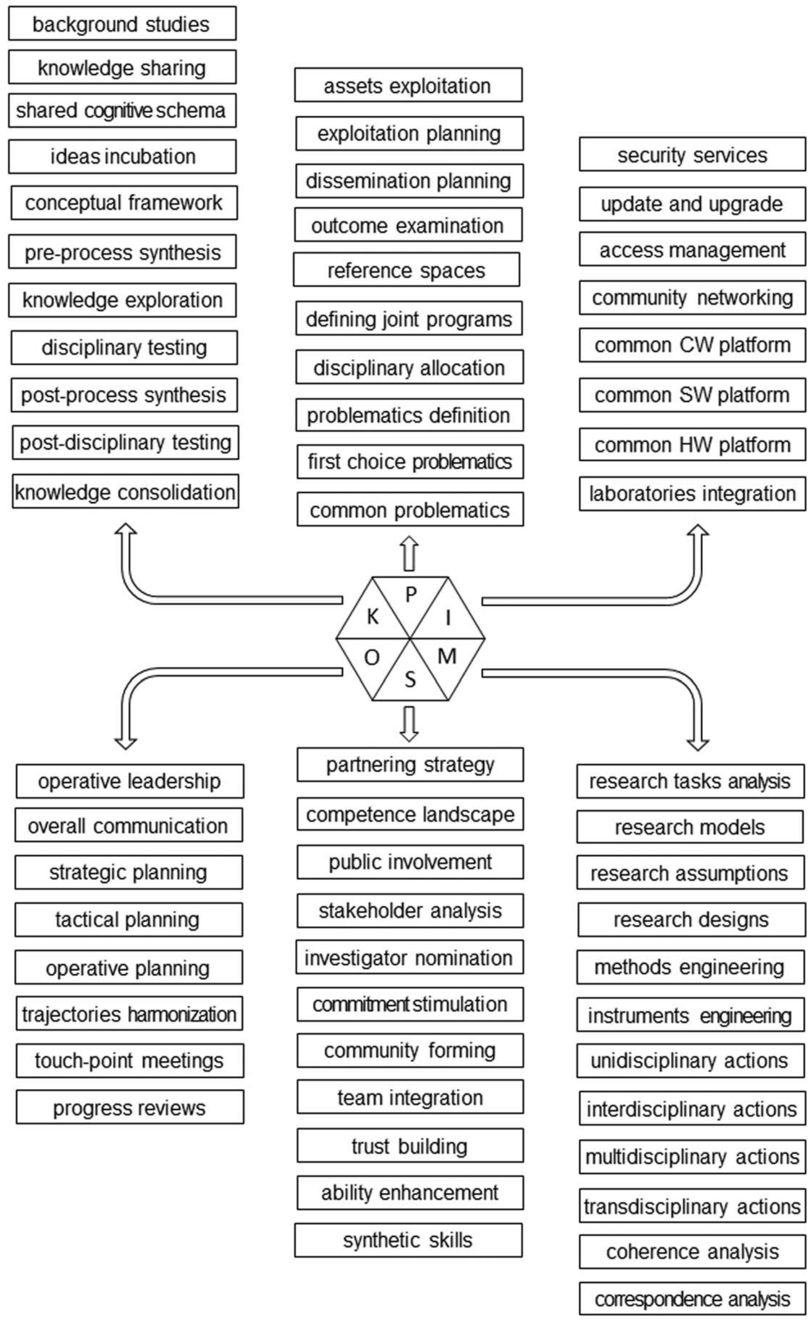

Fig. 8 The blueprint of the proposed supradisciplinary research framework

conceptualization and design of new cyber-physical systems, such problematics and/or phenomena can be such as: (i) exploring social demands in the light of the current technological affordances, (ii) exploring application opportunities for a family of smart (aware and adaptive) CPSs, (iii) ideation of next-generation home-care servicing CPSs with alternative cost profiles, (iv) aggregation and distribution of synthetic system knowledge from and to a fleet of CPSs, (v) intellect resource warehouses and upgrade mechanisms for self-evolving CPSs, and (vi) complex solutions for transferable cyber-physical–social–human systems, and so forth.

7 First Reflections and Possible Follow-Up Research

A novel narrative is emerging for twenty-first-century science that believes in interpersonal transactions while working in teams and communities, as well as in active engagement of public stakeholders by researchers in research programs or projects addressing socially based problematics [58]. The objectives of these postdisciplinary research approaches are to (i) holistically investigate and resolve complex problematics of the real world, (ii) provide different perspectives on and approaches to such complex problematics, (iii) offer holistic theories to answer research questions posed by multiple disciplines, (iv) develop consensus about definitions, principles, and guidelines to deal with non-reducible complicated systems, and (v) provide novel and comprehensive services for knowledge exploration and synthesis. In this position paper, we are interested in the concepts of pluridisciplinary and postdisciplinary research approaches, their methodological and epistemological features, and operationalization of supradisciplinary research in the specific context of cyber-physical systems. Based on informed assumptions, a six-pillar conceptual framework has been proposed. It clarifies the concerns associated with the establishment and execution of community-based supradisciplinary research programs/projects. Though the framework has been developed with a view to the specific application field, it is general enough to be transferable to other similar fields with or without adaptation.

The framework rests on six generic pillars: (i) problematics, (ii) infrastructure, (iii) methodics, (iv) stakeholders, (v) operations, and (vi) knowledge. It specifies the major concerns that have to be taken into consideration in a systematic manner in developing executional scenarios for supradisciplinary research. The framework arranges the concerns in a procedural logic—as they should be considered by the research managers and cyber-physical system developers. Though its importance is recognized, the framework does not cover the specific societal and personal issues of a successful organization of the inquiry at individual researchers, research teams, and research community levels in its current form. Notwithstanding, the framework can facilitate (i) management of research program and project organization tasks, (ii) joint formation of shared research infrastructure, (iii) setting up concrete research programs, projects, and processes, (iv) academic partnering and public stakeholder involvement, (v) process flow management and capacity/competence allocation, and (iv) knowledge synthesis, assessment, and consolidation in a holistic manner. Application and testing of the framework cannot be done by a single researcher. Therefore, the follow-up operative research must be organized on the basis of involving multiple research teams or a research community.

It is generally known that there is no effective innovation without new knowledge. It is not possible to go beyond the capabilities of current engineered systems and to ideate and conceptualize innovative systems without doing intensive research. However, doing such research is not trivial due to the growing overall complexity, functional and technological heterogeneity, and knowledge-driven nature of engineered systems. The acceptance of transdisciplinary research is negatively influenced by (i) the growing versatility of professional knowledge and complexity of academic cooperation, (ii) the historical compartmentalization of the scientific landscape, (iii) the sectoral division of responsibilities in contemporary society, and (iv) the increasingly diverse nature of the societal contexts. Supradisciplinary research opens up a multi-dimensional space of inquiry that is characterized by (i) concurrent dependence on multiple (physical, biological, human, social, computational, technological, etc.) domains of inquiry and investigations, (ii) various progression levels (discovery, description, explanation, prediction, and regulation) with regard to the studied phenomenon (problems), and (iii) need or synergy in terms of hardware, software, cyberware, brainware, etc., related knowledge.

Having read the text, the reader has most probably understood that there is a paradoxical situation concerning the framework. The author is also aware of this. The origin of the paradox is the juxtaposition of the form of the inquiry used to produce knowledge for the cognitive framework and the form of the work that would have been needed for a full-scale operationalization of the framework in practice and to validate it through its implications over multiple application cases. The inquiry could be done by one individual investigator who has sufficient knowledge of multiple disciplines (domains of interest) such as research theory and methodology, engineering and technologies of cyber-physical systems, and systems science and thinking [59]. The combination of these bodies of knowledge resulted in the discussed concept and content of the conceptual framework for operationalization of supradisciplinary knowledge. However, contradictorily, the concretization and execution activities implied by the conceptual framework could not be completed by one single researcher, no matter what application fields would be considered. The projection of the contents of the conceptual framework to real-life problematics and completion of the necessary supradisciplinary research would have needed multiple collaborating research teams or even a research community. For this reason, the contents and implications of the proposed framework have not been rigorously scrutinized. Unfortunately, this paradox cannot be resolved in this position paper.

One of the peer reviewers, as well as the corresponding guest-editor, suggested me to add a paragraph in this conclusive section that provides connections to computational methods and tools being developed for i*CPSs. In my view, the real issue is not only the availability and quality of tools for i*CPSs development but also the availability of tools dedicated to supporting collective supradisciplinary research. According to my best knowledge, due to the novelty of these problematics, such tools hardly exist if we ignore the computer- and network-based tools developed for designing and analyzing hardware, software, and cyberware for so-called "traditional" CPSs, and for validating system behavior from various engineering aspects. On the other hand, time has come to conceptualize computational tools that can robustly interconnect the knowledge and methods of multiple disciplines and, at the same time, can help designers and developers cope with the transdisciplinary complexity and heterogeneity. The currently used research tools can be applied invariably to specific research tasks, but we also need tools that can support organization and procedural management of supradisciplinary programs and projects throughout their complete lifecycle, and that can support the challenging process of: (i) creating joint intellectual spaces, (ii) maintaining the commitment of individuals of heterogeneous research communities, and (iii) fostering rapid epistemic translations. What makes the development and use of such computational tools complicated is that they cannot ignore the social and personal components of intellectualized system operations and doing supradisciplinary research in pluralistic contexts, respectively.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

No data, models, or code were generated or used for this paper.

Nomenclature

CPS(s) = cyber-physical system(s)
i*CPS(s) = intellectualized CPS(s)
BANGM = bits–atoms–neurons–genes–memes

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