Deriving Manageable Transdisciplinary Research Models for Complicated Problematics Associated with Next-Generation Cyber-Physical Systems:

Part 1 - Theoretical and Methodological Foundation

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Abstract: *There are many large-scale, transdisciplinary research problematics associated with next-generation cyber-physical systems, which are difficult to capture, analyze, and transfer into sharable research models. This two-part paper is intended to contribute to a better understanding and to provide a systematic approach to describing, scoping, and specifying manageable contents for transdisciplinary research models. Part 1 of the paper analyzes the essence and the interplays of the most important current trends, and creates a robust theoretical and methodological foundation for capturing and scoping research problematics associated with the evolving paradigm of cyber-physical systems. The elaboration and deployment of the proposed approach are discussed in detail in Part 2. Besides the overall procedural framework of the proposed holistic systematic combinational breakdown, all steps are explained and exemplified in an illustrative real-life example. The discussion in both Parts concludes with a number of propositions and further research opportunities concerning the theoretical and methodological foundations.*

Keywords: Megatrends, transdiciplinary, supradisciplinary research, cyber-physical-social-human systems, research problematics, complex, scoping process, research models.

1 Introduction

This paper addresses a hot issue of present day research theory and methodology which concerns transdisciplinarily conceptualized and supradisciplinarily organized inquiries into large-scale, technologically, industrially, and/or socially created, multi-faceted problematics such as increased population density, excess usage of personal communication devices, uncertainties caused by artificial intelligence, reduction of air pollution, electrification of transportation, highly transdisciplinary systems, and so forth. “No single discipline can resolve these cross-disciplinary problems on its own” (Ford and Ertas 2024). The number and extent of these problematics are gradually increasing. Due to their characteristics, they are not only difficult to conceptualize and model, but also challenging from a research methodological viewpoint (Galukhin et al. 2022).

The completed research regarded transdisciplinarity as an epistemological (and sympérasmological) issue that offers a new vision of nature and reality (Brenner, 2013), and supradisciplinarity as organization and managerial issue leading to a postdisciplinary, collective, and socialized conduct of research (Balsiger 2004). In definitions, transdisciplinarity, as practice of research, is defined by a few features such as (i) focusing on socially relevant issues, (ii) respecting the diversity of perspectives, (iii) transcending and integrating disciplinary paradigms, (iv) doing participatory research, and (v) searching for a unity of knowledge beyond disciplines (Pohl 2010). The managerial tasks are related, among others, to collective research model and research design development, and to establishing highly informed and creative communities and environments. Besides making an attempt to understand the essence and influences of the current, interrelated megatrends, the research reported in this paper also aimed at providing procedural support and computational means to conducting studies within supradisciplinary frameworks and collective scenarios. Having recognized the difficulties originating in epistemological and organizational complexities of supradisciplinary inquiries, it focused on designing and testing a procedure to systematically funneling initial research problematics into manageably-sized definitive research problematics and to deriving multiple research models for them. Though these efforts are absolutely necessary, the literature hardly goes beyond addressing some theoretical and epistemological issues (Lawrence 2015).

This paper tackles complicated technologically- and socially-rooted problematics which go together with epistemological (knowledge gap), methodological (missing methods), and pragmatic (feasible solutions) challenges. In our era, design problems are evolving into such socio-technical problematics characterized by fuzzy boundaries and an undefined center of gravity. Cyber-physical systems (CPSs) are not exemptions. Well beyond mechatronics, the discipline of CPSs is a truly open field from many aspects (functional, architectural, cognitive, social, etc.) and its identity transcends the limits of multiple thematic identities (Berian and Maties 2011). The transdisciplinary nature of CPSs is rapidly growing, and the move to next-generation CPSs (NG-CPSs) lends itself to such complicated problematics, e.g., the influence of intellectualization on human roles, social embedding of heterogeneous systems of CPSs, and maintaining positive developmental intents. However, to understand the essence of such problematics and to find technologically and economically feasible, human- and environment-focused design solutions, transdisciplinary teams formed by designers and other stakeholders need to acquire pertinent (newly explored or synthesized) knowledge, as well as to apply systems thinking and design thinking in combination. In this context our work represents a pioneering endeavor crucial for expanding the boundaries of knowledge and the range of methods - in particular, related to designing next generation cyber-physical systems.

To concurrently support a detailed discussion of the conceptual fundamentals and the proposed procedural framework and its application, respectively, the paper has been divided into two parts. The dual objective of Part 1 is to analyze the essence and interplays of the most important trends, and to create a thorough and robust theoretical and methodological foundation for capturing and scoping research problematics. Accordingly, an attempt is made to cast light on the trends of: (i) the evolution of the modes of science, (ii) the developments of research objectives and approaches, (iii) the emergence of overall research problematics (ORP) as complements of research phenomena, (iv) the shifting paradigms of cyber-physical systems (CPS), and (v) the growing need for systematic capturing and scoping of research problematics. In addition to having a glimpse on the traditional approaches to systematic inquiry, issues such as (i) knowledge synthesis for and by supradisciplinary research, (ii) procedural framework for supradisciplinary research, (iii) organizational, management, and social aspects, (iv) building shared intellectual spaces, and (v) limits and obstacles of post-disciplinary inquiries are briefly discussed in Part 1, while the proposed approach is presented and applied in Part 2. The whole process is decomposed into four stages, including (i) capturing the initial research problematics (IRP), (ii) devising scoped research problematics (SRP), (iii) synthesizing multiple definitive research problematics (DRP), and (iv) specification of detailed research models (DRM. This funneling can be easily grasped by a geographical analogy: ORP is the analogue of travelling to the USA, IRP is visiting New York, SRP is finding the Central Park, DRP is about locating, among the many banks in the park, the one on which someone is sitting. The DRM is a symbolic and textual sketch depicting this.

The primary sources of the input knowledge for the research reported in Part 1 were literature study and critical systems thinking (Richmond 1993). The starting points for Part 2 are the bodies of knowledge related to (i) the systematic combinatory breakdown (SCB) method published previously for analysis of research phenomena (Horváth 2017), (ii) the theory of multi-level holistic reasoning (Esfeld 1998), and (iii) the research methodological concepts, principles, and mechanisms associated with supradisciplinary research (Horváth 2023). Both parts provide a set of concrete propositions concerning the theoretical and methodological foundation, and the elaboration and deployment of the proposed funneling approach, respectively. In addition, further research opportunities are also proposed in both contexts. The stepwise execution of the procedure, and the input and output data have been included in a 30-page long research report titled "Operationalization of the procedural framework proposed for holistic systematic combinatorial breakdown of complicated research problematics". This report can be accessed at the following link: https://doi.org/10.13140/RG.2.2.22179.84003. One of the goals of providing access to this report was to offer insight in those outcomes of the completed research, which could not be included in this paper due to obvious space limitations. The other goal was to align the paper with the principles of the FAIR (Findability, Accessibility, Interoperability, and Reproducibility) initiative which advocates dedicated domain repositories for research data.

2 Evolution of the Ideologies and Modes of Science

Science is a historically evolving social construct that is strongly influenced not only by ideologies, but also by intellectual and technological resources. Therefore, it has gone through various transformations since the time of the antique Greek science until the present day neo-post-modern science (Drotianko et al. 2022). Over the centuries, its approaches and means have been radically changed from (i) naïve (discovering natural phenomenon by incidental observations), through (ii) empirical (describing natural phenomena by repeated practical studies), (iii) theoretical (mathematical modeling and generalization of natural phenomena), (iv) computational (algorithmic simulation and generalization of complex phenomena), and (v) data-driven (data-intensive statistical exploration of distribution patterns and relationships), to (vi) problematics focused and generative computational intelligence-assisted (synthesizing solutions for non-naturally existing complex challenges) manifestations (Figure 1). Certain science philosophers argue that science has experienced a more profound transformation in the last century, then ever before.

The continual change of sciences is a normal phenomenon. However, the remarkable pace and extent of the changes observed over the last century are truly astonishing. In addition to acceleration, transformations occur across multiple dimensions. Concurrently, there are changes in the approaches and the means of disciplinary inquiries too, and an all-embracing societal embedding of science is also taking place (Benard and de Cock-Buning 2014). Furthermore, the professional and societal relations of science and the role of knowledge are also changing. From the 17th century to the end of the 19th century, the classical science insisted that knowledge (and methods), on the one hand, should be independent of the subjects who conduct research and present knowledge about the studied phenomena, and, on the other hand, should be independent of the objects 'as they exist by themselves' (Kauffman 2017). From the mid of the 20th century, the non-classical science epistemology regarded knowledge as a result of scientific inquiries that are dependent on the means of observation (including researchers), and advocated testing of knowledge to qualify as scientific (Cellucci 2015). Having

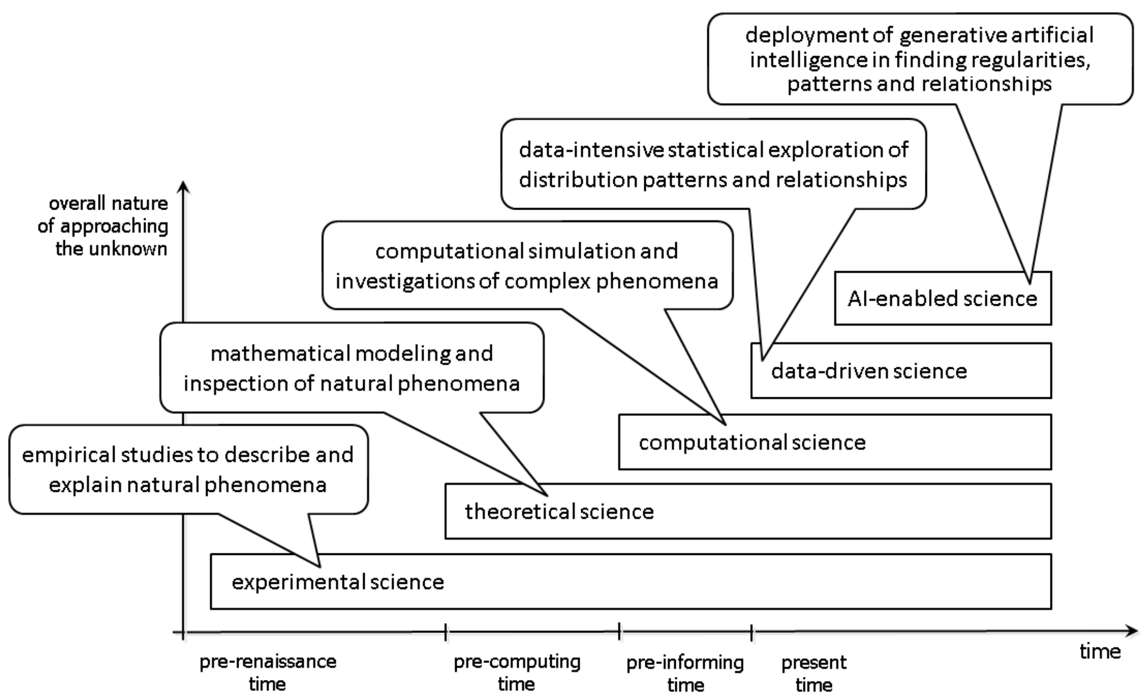

Figure 1: Genres of scientific inquiries.

emerged in the mid-20th century, the so-called post-non-classical science recognizes that, on the one hand, knowledge includes multiple ideals and types; on the other hand, it reflects various worldviews, perspectives, and outlooks on both the subjects and the investigators (Gergen 1985). These influential factors together, combined with the triggered uncertainties, have created an uneasy situation.

The current neo-post-modern science (NPMS), which is still in the stage of formation, simply claims that knowledge is what serves a purpose (de Saint-Laurent et al. 2017). Due to the accelerated paradigmatic changes, it often has no time to exhaustively describe, explain, predict, and/or regulate the object of research. One reason is that the object of research is also tendentiously changing from naturally existing phenomena to industry- and/or society-created complex problematics. Therefore, the doctrine of NPSM must also focus on (i) understanding these problematics, (ii) finding solutions for the most critical elements, or for the whole of non-naturally existing complicated problematics, and (iii) involving social actors in the knowledge generation processes in appropriate ways. By doing these, NPMS actually prefers impacts to insights (Cruickshank 2016). As a combined ontological and epistemological trend, this is often referred to as moving from the bedrock of traditional Mode 1 science to that of a modern Mode 2 science (Gibbons 2000).

3 Developments with regard to Research Objectives and Inquiry Approaches

The above summarized ontological and epistemological changes do not leave the methodological foundations of NPMS untouched. In simple words, both the objectives and the approaches of doing scientific inquiry are changing, though the approach of studying research problematics follows the traditional ‘ladder of knowing’ which is often used to explain the progression of inquiry in naturally existing phenomena (Figure 2). However, what can be observed from a birds-eye-view is that the earlier distinguished basic, applied, and operative research categories are not only getting closer to each other, but also have actually started to blend into an integral category of research. An immediate effect of it is having rigorously verified and validated chunks of hard knowledge, incomprehensively consolidated chunks of soft knowledge, and intuitively validated chunks of human tacit knowledge together in an amalgamated manner, as a mixture (Horváth 2022). Reflecting our understanding, a simplified progression model (procedural flow) of transdisciplinary research is shown in Figure 3.

It can also be observed that, the boundaries of the traditional disciplines become blurred or even demolished in the process of formation of interdisciplinary and transdisciplinary research domains and disciplines (Vajaradul et al. 2021). McGregor (2018) explained four philosophical frameworks (ontology, epistemology, logic and axiology) as shaping factor in transdisciplinary research methodologies. The accompanying ontological, epistemological, and methodological changes are identified as scientific convergence. At the same time, in the integrated fields, brand new interest domains and disciplines are popping up continuously. This divergence manifests as the dialectic counterpart of scientific convergence. Due to the growing heterogeneity and complexity, there is a growing need for organizing unidisciplinary and pluridisciplinary research programs and projects into supradisciplinary epistemological, methodological, and organizational frameworks (Hoffmann et al. 2017). Another driver behind this is the growing demand for transdisciplinary knowledge in order to successfully address complicated problematics.

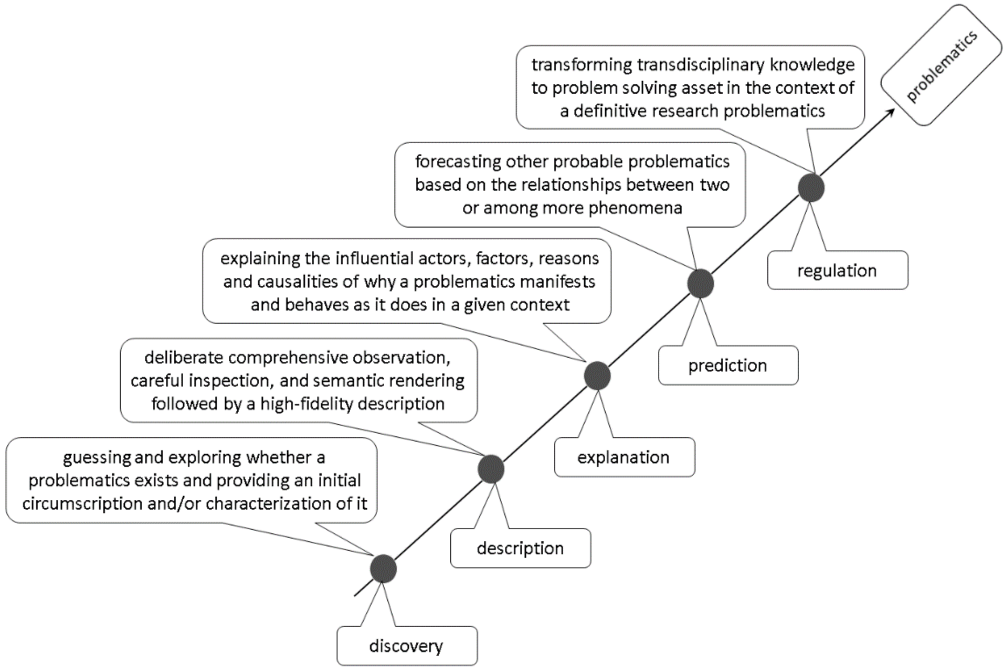

Figure 2: The ladder of knowing research problematics.

The cognitive facilitation and organizational establishment of supradisciplinary research (SDR) is shown in Figure 4. SDR exposes a multi-dimensional investigation characterized by (i) coexisting dependence on multiple domains of inquiry (physical, biological, human, social, computational, environmental, technological, etc.), (ii) divers progression levels (discovery, description, explanation, prediction, and regulation) with regards to the investigated phenomena and problematics, (iii) synthesis and synergy of intellect over multiple disciplines, and (iv) integration of knowledge concerning hardware, software, cyberware, mindware, orgware, etc. constituents of systems (Horváth 2023). Contrary to the efforts, the landscape of SDR shows many grey or white spots in terms of procedural frameworks, approaches of knowledge synthesis, and combination of mental models (Defila and Di Giulio 2015).

Mode 2 science considers research as a socially-based dynamic enterprise, whereas SDR attempts involving social stakeholders both in the conduct of research and in the utilization of research results. Practical organization and execution of SDR in complicated problematics has multiple demands. First of all, it necessitates devising high-resolution procedural frameworks and logically and makes temporally sequenced, collaborative activity scenarios indispensable. A proper procedural framework has to rest on the followings conceptual pillars: (i) the investigated complex phenomena, (ii) the integrated and shared infrastructures, (iii) the applied research methodics, (iv) the involved academic and industrial stakeholders, (v) the establishment and execution inquiry and operations, and (vi) the input and output knowledge (Horváth 2016). It also needs the consideration of all influential social/societal aspects (that are in fact central in or related to many research topics). In the first run, this latter means two things. On the one hand, it facilitates conducting SDR programs/projects with a view to the specificities of one or more target applications. On the other hand, it demands that the mid-term results and the final outcomes of SDR programs/projects should be not only verified, but also

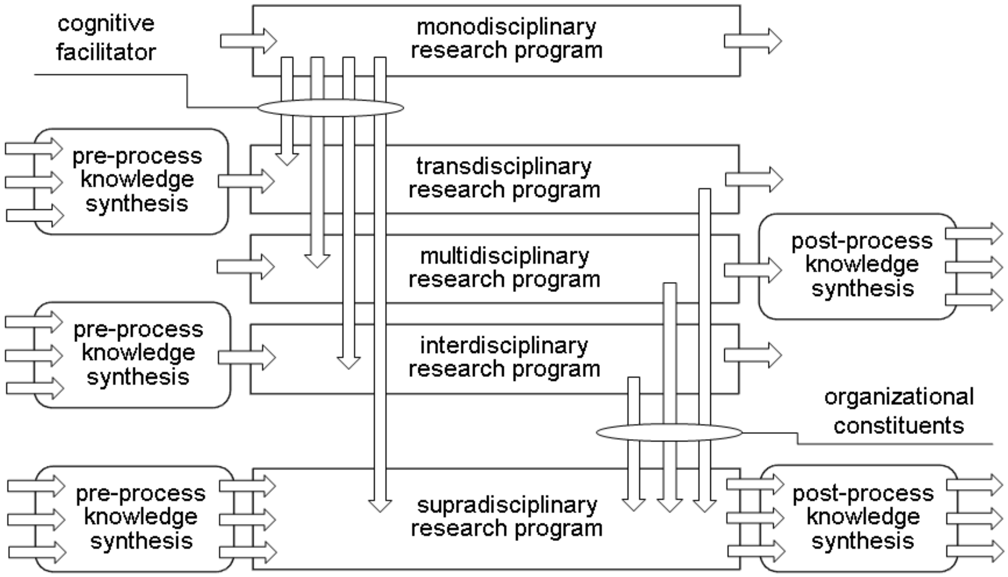

Figure 4: Cognitive facilitation and organizational establishment of supradisciplinary research.

validated and consolidated in social/societal perspectives. This latter is important since scientists typically argue about professional and logical verification of their theories, but the society may have a different opinion, or may even be skeptical, about their value and utility in particular social/societal contexts (Funtowicz and Ravetz 1993).

Societal acceptance may not be achieved straightforwardly when not only novel theories, but also new technologies are concerned. It is known both from the literature and from the practice that certain technologies, such as energy from biomass and gene technology, have not been socially accepted even though their utility has been shown by scientists. These call the attention to the importance of avoiding possible discrepancies between scientists and society (Canton 2004), SDR requires not only collective approaches for investigation, but also efficient working strategies and tactics for integration of knowledge from multiple disciplines in a coherent and synergistic way, as well as a pool of shared and complementary research methods (Zhang and Mei 2020). In addition, it is supposed to view problematics not only from viewpoints of the sciences, but also from the perspective of usefulness and effectiveness of the generated knowledge in practical application (Tebes et al. 2014).

SDR practically equals the importance of construction of disciplinary knowledge with exploration of disciplinary knowledge in view of resolving complicated problematics and finding operative solutions for the involved (transdisciplinary) problems. To be efficient, it imposes the view of holistic constructivism on complicated problematics characterized by an abundant amount of factors and parameters. A holistic view, imposed on multiple levels of analysis and reasoning, facilitates (i) integration of diverse disciplinary knowledge, (ii) addressing complex component problems, (iii) uncovering patterned and emergent properties, (iv) transcending reductionism and fixation, and (v) ensuring high practical relevance. It also enables researchers to navigate the complexities of supradisciplinary research and contribute to a more comprehensive understanding and resolution of the problematics at hand. For this reason, holistic intuitive constructivism will be operationalized in Part 2.

Notwithstanding, holism is seen as reversed reductionism by some systems researchers, that is, explaining the components and their and relationships based on the general characteristics of a system, rather than explaining a system in terms of the characteristics and relationships of its components. While reductionism decomposes the whole into its explicit constituents, holism – theoretically - tackles the whole by systematically abstracting implicit constituents starting out from the explicit constituents, called instance constituents (Havlík 2022). They embed information about things, attributes, relations, and implications. The purpose of the abstracted constituents is to capture those pieces of information and intricate relationships which actually lend themselves to a holistic view. Called general/abstract constituents, these are intuitively derived by aggregating, integrating, and abstracting information on and above the level of instance constituents, without any limitation of the scale of abstraction.

The epitome of SDR is deemed trustful and feasible, and its capability to allow post-disciplinary investigations based on unbiased preliminary and subsequent knowledge synthesis is recognized in the literature. In combination with the growing need for cross-disciplinary integration of knowledge and methods, the inclusive trend of scientific convergence increases the importance and triggers the development of team- and community-based research approaches. This, in turn, implies the need for overstepping the cultural boundaries of research by producing knowledge through coordinated transactions of all stakeholders and project management (Mobjörk 2010). As an integrative concept of facilitation of complex problem-solving, SDR (i) establishes research communities of enhanced social skills, (ii) operates with both a priori and posterior integration of knowledge of confounding disciplines, and (iii) complements the competences of researchers representing different disciplines to address large scale problematics on multiple levels.

4 Emergence of the Concept of Research Problematics as a Complement of Research Phenomena

The words ‘phenomenon’ and ‘problematics’ are sometimes interchangeably used in the literature to refer to certain issue or topic chosen as subject of investigation (van de Ven 2016). Independent of their actual essence, we regard problematics as complement of naturally existing phenomena. The word 'problematics' appeared in the American English in the period 1955-60 to express the uncertainties, difficulties, and challenges of constructed situations or plans (Pohl 2005). In simple words, problematics is an agglomerate of conceptual heterogeneity, interplaying problems, lack of overall comprehension, and managing difficulties created by industries or societies. In the interpretation of this paper, problematics are conceptual renderings of societally-based and orientated, large-scale, and challenging real-life situations that are characterized by transdisciplinarity, dependencies, and compositionality (Pohl and Hadorn 2008).

Like a complete description of a research phenomenon, a complete characterization of a research problematics would need an infinite number of pieces of information. Due to the unmanageability of this, a rendering of an overall problematics is always incomplete and subjectivity-dependent. Such complicated problematics often require input from multiple disciplines such as physics, biology, engineering, computing, social sciences, etc. In addition, while research phenomena are typically handled according to the principles of reductionism a complicated problematics usually cannot be treated in a reductionist manner. Characteristics such as internal transdisciplinarity and compositionality, and interplaying external dependencies cannot be decomposed (Tripakis 2016).

Therefore, problematics represent challenges for science, research, and development, as well as for society, industries, and businesses. Consideration of social/societal aspects as part of the investigated problematics increases the overall complexity, calls for holistic approaches, and needs collaborative efforts (Sztipanovits et al. 2019).

For the reason that problematics are either unintentionally constructed or triggered to emerge, their internal construction is an important matter. As touched upon above, reductionism usually treats phenomena as composable systems. Composability, as a system property, is predicated on the assumption that the properties of components remain unchanged through interactions with other components (Kopetz 1998). Enforcing the principle of composability, reductionist investigations ignore or struggle with explicit and implicit interrelatedness, confounding, and perplexing on system level. Recognizing the role of these characteristics, a holistic investigation tries to capture these through considering a problematics as a compositional system. This means that compositionality is becoming one of the most crucial concepts not only in modern systems thinking, but arguably also in constructive research methodology (Li 2019). Eventually, compositionality boils down to both epistemological and social issues. On the epistemological side, research teams and collectives involved in supradisciplinary research should strive for achieving compositionality in knowledge by synergistically integrating knowledge of the involved disciplines and to derive a holistic view based on this. On the social side, they should strive for learning the working and thinking cultures of the other parties, integrating diverse perspectives, establishing effective communication channels, fostering open dialogues, and leveraging strengths by moving towards coadunation in their research projects (Forscher et al. 2020).

Our basic assumption is that research problematics can be captured and semantically rendered based on the principal constituents that were proposed for the description of research phenomena. The concerned logical decomposition and re-composition process has been published by Horváth (2017). Semantic mechanism of capturing the constituents of a complicated research phenomenon assumes that (i) objects existing in the natural (materialized) world can be captured as things in the semantic space, (ii) all things can be characterized by a unique, finite set of intrinsic attributes, (iii) depending on their 'teleological' manifestation and characteristics, things can be in multiple relations, and (iv) based on their attributes and relations, things have causal implications (effects) in separable from their ends or utility. This reductionist view allows not only a decomposition of a complicated phenomenon, but also the extraction of partial phenomena that are molten in the complexity of the considered overall phenomenon. This process is named 'systematic combinatory breakdown' (SCB) method. With the necessary adaptations, the logical principles and mechanisms could be adopted as the basis of a procedural framework for a systematic investigation of research problematics. Figure 5 shows the conceptual framework (the schematic principle) of capturing research problematics.

Intuitively, successful treatment of complex, heterogeneous and compositional problematics necessitates viewing and capturing them as wholes, rather than dissecting them into parts. This is the primarily reasons why adaptations are needed in the SCB method. However, the intended holistic capturing and rendering is not trivial due to two influential factors: (i) the parts of a whole are in intimate interconnection, such that they cannot be understood without reference to the whole, and (ii) the semantic interconnection of the parts can be seen, in principle, from infinite number of perspectives and abstraction levels. These cannot be supported even by modern computational mechanisms and algorithms. Consequently, simplifications are also needed. In the adaptation of the SCB, this simplification meant that only two perspectives have been assumed, that is, an instance level view and a generalized/abstracted level view, without specifically defining the semantic disposition of the deployed generalization and/or abstraction. A detailed articulation and specification of the possible levels of the generalized/abstracted semantic continuum would require further cognitive studies. That is to say, the proposed quasi-holistic representation scheme assumes the concurrent consideration of the constituents of problematics on a definitive instance level and on an intuitively interpreted holistic level. The latter is populated by various generalized and/or abstracted concepts of constituents.

Capturing research problematics is a multi-stage process requiring multiple intuitive decision-making. Its specification happens relative to a local world with tentative boundaries. This includes two spaces, (i) the observational space which is populated by instance constituents, and (ii) the rational space which is populated with general/abstract constituents. The two semantic spaces are bridged by the concept of things. It means that instance things and general/abstract things jointly form the reasoning platform for rendering and scoping targeted research problematics. While the constituents are defined independently in the process of specification, they are concurrently considered in the proposed holistic systematic combinatorial scoping method. The jointly considered implications of the attributed and related instance things and general/abstract things result in knowledge that can be investigated towards resolving the challenges carried by the scoped problematics. In this context, the importance of dynamic engineering, design, and management knowledge integration cannot be underestimated (Tate, 2010).

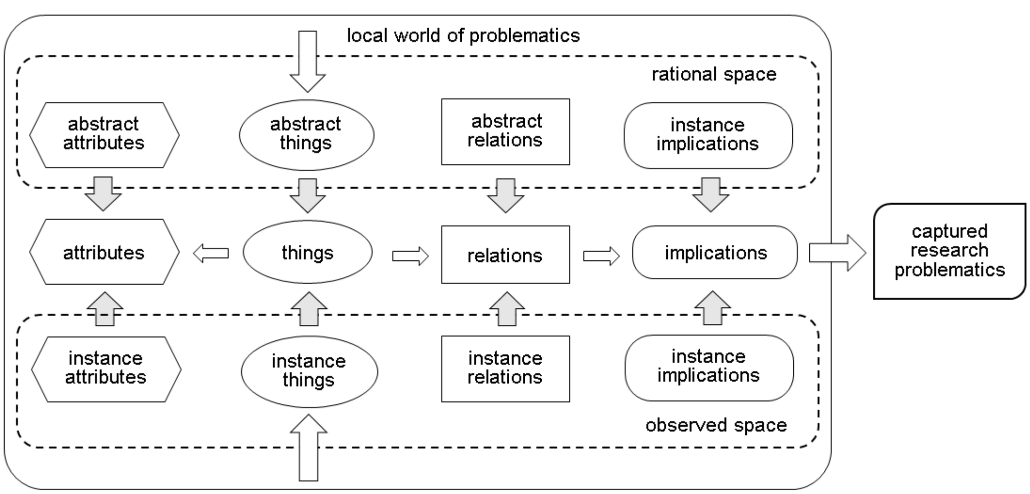

Figure 5: The principle of capturing research problematics.

5 Shifting Paradigms of Cyber-Physical Systems

Since the word ‘paradigm’ is often-used and heavily overloaded with multiple meanings, it is expedient to clarify its essence in the context of cyber-physical systems. In its most general meaning, it is a belief system, but also a manner of thinking or doing things based on intelligence and assumptions. The word ‘paradigm' also means a way of looking at something and a set of ideas in some perspective (Amrani et al. 2021). It is also used to express a generic pattern, a fundamental model, or a typical example of something. Therefore, we use the term ‘system paradigm’ to refer to a comprehensive constitutional pattern (or human mental model) that underpins all specific manifestations of produced things, such as artifacts, technologies, and infrastructures. This interpretation does not exclude any (non-deterministic) coexistence of multiple paradigms and does count on their time-related arbitrary or systematic strengthening or weakening. In this sense, this use of the term deviates from Kuhn’s theory of paradigms which posits that a new paradigm replaces the old one.

Eventually, system paradigms can be identified based on a finite set of indicators, such as (i) the basis of existence, (ii) the objectives of manifestation, (iii) the offered functional spectrum, (iv) the architectural organization, (v) the range of enabling technologies, (vi) the teleology of application, (vii) the possessed problem-solving intelligence, (viii) the doctrine of resource management, (ix) the range of adaptivity, and (x) the apparent operational characteristics. In the context of cyber-physical systems, these indicators are instantiated to become distinctive characteristics. Working within the conceptual boundaries of a system paradigm means that the curiosity and interest of researchers and developers are guided toward the same puzzling problematics. They can see the related theoretical, methodological, professional, and praxiological issues and problems from the same perspective, in the same way, and with the same objectives in mind (Rousseau 2019). While the initial formulation of the system paradigm of CPSs rested on the concept of juxtaposed interoperation, the currently dominant system paradigm emphasizes scientific convergence. Among others, it involves the synthesis of disciplinary knowledge, integration of implementation technologies, blending functional solutions, and harmonization of system characteristics. Therefore, it can be referred to as the convergence system paradigm.

However, as Heraclitus said, 'everything flows'. The only permanent thing is the change and this applies to CPSs too (de C Henshaw 2016). Published elsewhere, the results of our studies over the last decade indicate that we have reached the era of the second generation CPSs. These systems feature high level autonomy, smart behavior, and adaptation ability (Delicato et al. 2020). However, further evolution of these systems has started and actually happens in multiple dimensions. The fact of the matter is that actually four threads of evolutionary changes could be identified and prognosticated. The four threads are: (i) disciplinary complexification, (ii) functional intellectualization, (iii) canonical socialization, and (iv) adaptive personalization. They are shown and further articulated in Figure 6. While these developments extend the scientific, engineering, and praxiological scope of the discipline of CPSs, they are also transforming it into a pluridisciplinary field of knowing, doing, and making. The bodies of knowledge from scientific, technological, computational, human, and social domains are being integrated (Fantini et al. 2020). As a consequence, this family of systems combines not only physical (analogue and digital) and cyber (data, information, knowledge, algorithms, and mechanisms) components, but also extends to the human (perceptive, cognitive, behavioral, and emotional) space and the social (relational, cultural, normative, and valuation) space.

Disciplinary complexification is almost necessarily emerging in this field due to scientific and technological convergence and divergence, which are also strongly influenced by the progression of artificial intelligence and intelligent computing. Eventually, these offer opportunities for multi-aspect socialization and adaptive personalization of CPSs. Efforts are being made to develop and deploy cross-domain methodologies for analog and digital hardware, control and application software, data and knowledge cyberware, and structured collective brainware. At the same time, it is not fully transparent what the system paradigm of next generation CPSs will be (Hafner-Zimmermann and Henshaw 2019). These uncertainties have a vital impact on and pose new challenges for the research, development, education, and deployment of NG-CPSs. On a longer term, the mentioned causal relationships necessitate investigations according to the principles of complexity science which studies emergent affordances, non-linear behaviors, dynamic architectures, formative interactions, globalization of localities, synergistic intellect, and unpredictable characteristics.

Conjunction of knowledge, technologies, constituents, etc. also provides ground for emergence of novel compositions of fundamentals, mechanisms, and characteristics. This facilitates disciplinary divergence, which contributes to the shift (or evolution of the paradigm) as convergence does. The simultaneous and dialectic presence of conjunction and disjunction, or convergence and divergence, is a major source of uncertainties concerning the evolution of the paradigm of CPSs. The conjunction of the constituents of the physical, cyber, social, cognitive, and emotional spaces lends itself to the ontological divergence of human-physical-cyber, or physical-human-cyber, or physical-cyber-human systems versions of the paradigm. Contemplation of a convergence-divergence paradigm forwards us closer to real-life manifestation issues, whereas excluding the aspects of divergence reduces the chance of prognosticating possible trajectories of evolution of then paradigm.

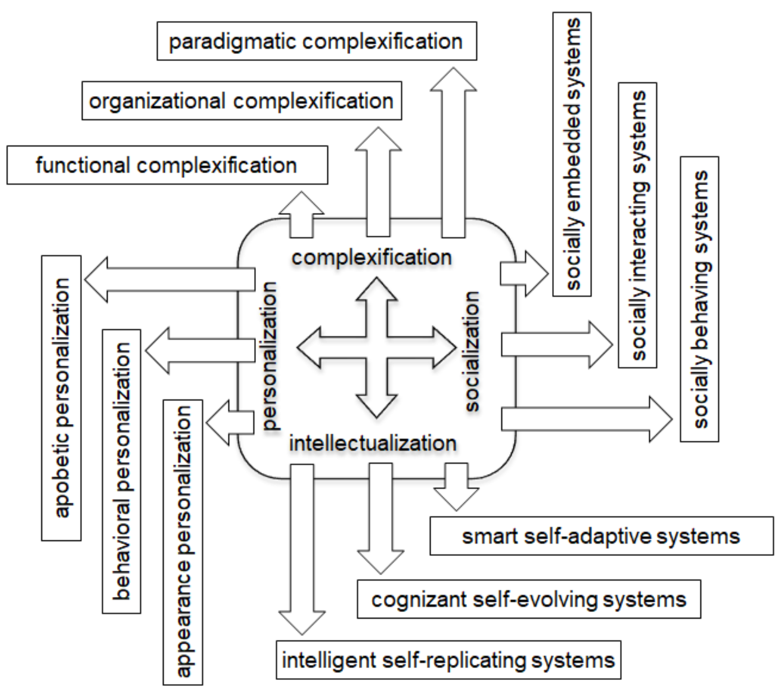

Figure 6: Paradigmatic evolution of cyber-physical systems.

CPSs are becoming artificial intelligence-powered and highly intellectualized from the perspective of complex problem-solving. Therefore, the somewhat paradoxical issue of transferred natural intelligence versus acquired synthetic intellect is also intensively disputed with regards to CPSs. There seems to be an agreement in the literature on that human (biological) intelligence can be roughly approximated in intellectualized systems by a blend of five different forms of computational intelligence, namely (i) data/information intelligence, (ii) perceptual intelligence, (iii) cognitive intelligence, (iv) autonomous intelligence, (v) emotional intelligence, or synthetic intelligence extending to all. An emerging specific dilemma concerning tomorrow's functional intellectualization of CPSs is the move from algorithmic intelligence to creative linguistic intelligence. It is debated if the emergence of the latter creates only a complement or an alternative of the former.

Next-generation CPSs are envisaged as synthetic intellect-based systems which should self-generate or self-acquire problem-solving knowledge and ampliative application-specific reasoning mechanisms on their own in order to maintain their problem-solving and self-management abilities. These systems are initially intellectualized by human-aggregated data, information and knowledge, but they are supposed to extend their abilities significantly during operation. The related literature advises that, in overall, the scientific research enterprise is facing a dual challenge concerning the problematics of creating and deploying next generation CPSs. On the one hand, research is supposed to intensify inquiries into transdisciplinary natural and social phenomena. On the other hand, it is expected to address complicated problematics, which are jointly created by the industry, society, and human individuals. Such dual-aspect investigations necessitate supradisciplinary programs and projects which equally count on the insightful cooperation of academic and society stakeholders. Research for, in, and by the next generation of CPSs also necessitates the reconsideration of both disciplinary (foundational) and practical (operational) research approaches. Further efforts are needed to describe the identity characteristics of synthetic knowledge, to work out the principles and mechanisms of its management, to explore the new challenges, affordances, and benefits of this new asset throughout the whole industry and daily life. The necessity of autonomous computational knowledge aggregation, transfer, and blending approaches is evidential.

6 Need for Systematic Capturing and Scoping Research Problematics

As the preceding sections underline, doing inquiries to resolve complex problematics, such as those associated with NG-CPSs, is a convoluted and challenging task. It originates partly in the need for a proper set up, organization and execution of a socially extended supradisciplinary research, but also in the typically large-scale, cross-disciplinary, and complicated nature of research problematics themselves. A vaguely emerged research problematics should be, first, conceptually grasped, and then transferred into a specification that can be the basis of systematic studies (Gunasekaran et al. 2015). Traditionally, this specification of the object (contents) of research manifests in research models (RMs). Procedurally it means that an overall research problematics (ORP) should be transformed into a shared research model (SRM) that is the primary source of information for organizing supradisciplinary research programs and projects. The transformation is a multi-stage procedure, having descriptive and/or constructive steps in each stage. This semantic procedure can be facilitated by a symbolic representation of the elements of the problematics and the transformative operations.

Achieving the stated professional goals, SDR needs novel procedural (organizational and management) frameworks which are tailored to the target application domains and cover the societal and personal issues related to them. The central issue of the background research was to devise a procedure for the development of holistic research models for SDR in highly complex, multiple interest fields-related, and socially-rooted problematics. To get to this end, (i) the principles of doing SDR have been regarded as a starting point, (ii) the analogy of complex research phenomena has been imposed on complicated research problematics, and (iii) an approach to holistic funneling of socially-based problematics has been operationalized. SDR involves different teams and communities of researchers in knowledge production processes, and harmonizes their goals with the expectations of other stakeholders (Tebes and Thai 2018). The basic objective is to generate solutions that can be agreed upon by the representatives of different disciplines. The latter is achieved by (i) holistically investigating complicated real-world problematics, (ii) approaching such complicated problematics from different perspectives, (iii) offering holistic theories to answer research questions of the concerned diverse disciplines, (iv) developing consensus in terms of definitions, vocabularies, principles, and guidelines, and (v) providing novel comprehensive methods and tools for knowledge exploration and synthesis.

We must bear in mind that research problematics typically manifest as a blend of some (i) unsatisfying circumstances, (ii) anomalies in arrangements, (iii) not wishful implications, and (iv) promising opportunities. The task of supradisciplinary design research is to discover and investigate the unknown elements of these factors and their combinations, and to explore and aggregate knowledge concerning their manifestations, relationships, uniformities, and irregularities. Systematic handling of problematics plays an important role in finding rational resolutions for their entirety or at least for their accessible parts. At the same time, scoping the content of the research to a manageable complexity and systematization of the approach of pluridisciplinary investigations are often overlooked or not fully understood. The former implies the need to develop supradisciplinary research models (SD-RMs), while the latter requires the development of supradisciplinary research designs (SD-RDs). The relationship of the research model to the research design is shown in Figure 7. Though these are equally important for a successful SDR, this paper restricts its attention to a systematic investigation of complicated problematics and to delimiting the scope of research to a manageable research model. The pragmatic goal is to help overcome the common mistake of researchers to start their investigation without a proper critical understanding their pluridisciplinary research topic(s) and blueprinting their collective approaches before starting the integration of their background knowledge.

The preliminary step of developing a scoping and modeling method was studying the results of forerunning research projects with regard to systematic investigation and complexity reduction in a holistic (non-reductionist) manner. Due to the scarcity of prospective propositions, we have decided to adapt the so-called systematic combinatorial breakdown (SCB) method, which has been developed for systematic investigation and specification of research phenomena (Horváth, 2017). We have adjusted the SCB-method to the study of complicated problematics and defined the specific operations needed for the semantic transformations. Intuitive reasoning is used in the selection of the most influential constituents, factors, and parameters. In addition to a tentative formal rendering, the main goal of the procedure is to (i) capture the ORP in a manageable initial research problematics (IRP), where $IRP \equiv ORP$ or $IRP \subset OPR$, (ii) extract a purposefully scoped research problematics (SRP) from the IRP so as $SRP \subset IRP$ and $\cup(SRPi) = IRP$, (iii) derive appropriate definitive research problematics (DRP) so as $DRP \subset SRP$ and $DRPi \neq DPRj$, and (iv) specify the research model of a DRPi (RMk(DRPi)). The set of operations needed in the stages of transformation are shown in Figure 8.

In Part 2, we present the procedural framework that supports systematic development and specification of scoped problematics for pluridisciplinary studies, as well as the deployment method implied by the procedural framework/ The method is referred to as holistic systematic combinatorial scoping (HSCS) of research problematics. The framework identifies 21 subsequent activity steps, which are also discussed in detail in Part 2. This involves all steps, from the specification of the instance and general/abstract constituents of this problematics, the intuitive reasoning about the importance of the constituents, and the combination of the two-level constituents to show the usefulness of the latter for holistic reasoning. Finally, alternative SRPs are intuitively derived, specified, and compared in terms of their research complexities and implications. In addition, we demonstrate the deployment of

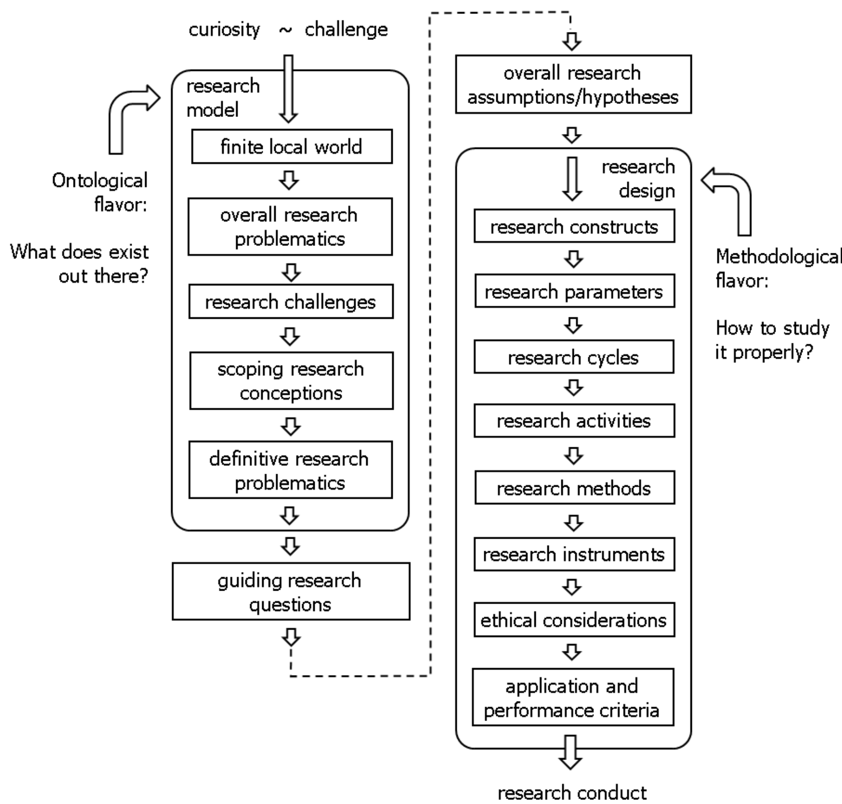

Figure 7: Transition from the research model to the research design.

the multi-step process. As a reference case, we present a small-scale explorative study which addresses the problematics of avoiding frequent accidents at an uncontrolled intersection in the suburb of a city. Following the same steps, the method can be up-scaled to much greater real-life problematics, though the amount of the needed work may grow non-linearly.

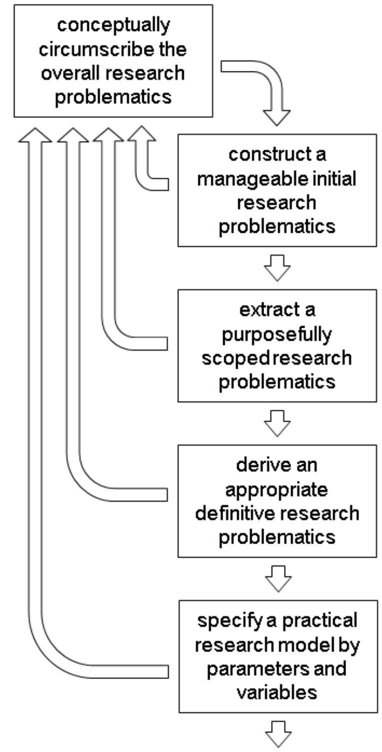

Figure 8: The transformational stages of an ORP into a RM(DRP).

7 Reflections and Conclusions

Our work suggests that proper research models for complicated problematics cannot be done without their formal representation and holistic treatment (Maydiantoro 2021). However, large-scale problematics often cannot be treated as a whole because of their inherent complexity. On the other hand, one or more "hot spots' can be found and localized practically in every complex problematics. The truth of this conjecture implies that the attention should be placed onto such hot spots, and this may avoid struggling with the unmanageable complexity of the overall research problematics. The holistic treatment can largely be maintained by treating the hot spots in the overall context of the problematics. This thinking is in the background of the proposed holistic systematic combinatorial scoping method.

Operationalization of the abstract concept of holism proved to be a serious sematic challenge for our work. There have been several reasons found for it. Holism can be seen both from an internal viewpoint and from an external viewpoint. From an internal viewpoint, it expresses synergistic relationship, mutual dependence, and mechanistic inseparability of the constituents of a problematics. From an external viewpoint, it means that all (or, at least, the most influential factors (constituents) should be taken into consideration. As touched upon above, the cardinality of such influencing factors can be large. Due to their intricate interconnections, the constituents cannot be investigated and understood without referring to the interrelated constituents or to the problematics as a whole. Eventually, this boils down to the issue of conceptual modeling of holism and to the issue of operationalization of the conceptual model in investigation of problematics.

Positive features of a holistic investigation are that it (i) operationalizes a big picture approach, (ii) assesses multiple factors influencing inside and outside a problematics, and (iii) facilitate the study according to multiple objectives and concerns. Negative features of a holistic investigation are that (i) working with many objectives, concerns, constituents, and characteristics makes the investigation complex, (ii) the investigation may overlook finer but influential details of the constituents, and (iii) thinking in broad perspectives makes scientific experimentation and testing difficult. In simple terms, no holistic view or analysis can cover all influential constituents of a problematics due to the concomitant complexity and the incurred infinite amount of information.. That is, holism cannot be operationalized without a semantic and cognitive simplification. Moreover, holistic analysis and scoping is a laborious process which should be tailored to meet the needs of concrete cases of processing complicated problematics for supra-disciplinary research

The work presented in this part of the paper extends the current knowledge concerning the issues mentioned above and calls for follow-up efforts toward testing the proposed framework in application domains largely different from and more complex than that were considered at deriving and demonstrating it. Though the need for it has been recognized recently, the transition from Mode 1 research approaches to Mode 2 research approaches will probably be slower than necessary (Bartunek 2011). The main new challenges both for the academia and for the concerned industries are such as (i) framing transdisciplinary research approaches, (ii) designing holistic research models, (iii) preparing supradisciplinary collectives for conducting research, (iv) applying supradisciplinary research organization and management, and (v) encouraging commitment to and desire for supradisciplinary research. It is appropriate to claim that executing such composite research is a complicated problematics on its own.

8 Propositions and Future Work

The research reported in Part 1 has attempted to contribute both to the understanding of the trends and to the methodology of systematic inquiries. We posit the following propositions:

- The major trends are (i) moving from Mode 1 (reductionist) science to Mode 2 (holistic) science, (ii) involving the broadest possible spectrum of stakeholders in exploration, synthesis, and utilization of contextualized knowledge, and (iii) dealing with not only nature- and society-rooted phenomena, but also industry, society, and human created problematics. As a consequence of the sudden and rapid changes, not only scientifically underpinned solutions, but also the concepts aiding systematic management of supradisciplinary research in complicated problematics are still scarce in the present-day literature.
- Research models and designs have moved out from the bedrock of unidisciplinary approaches but seem to get lost or at least hold up in the labyrinth of pluridisciplinary and postdisciplinary approaches. Time has come for researches to develop procedurally systematic and methodologically rigorous approaches to study and resolve complex, heterogeneous, intricate or even wicked,
- Research problematics distinguish themselves by their (i) complicated nature, (ii) disciplinary heterogeneity, (iii) socio-technological roots, (iv) physical and logical interconnectedness, (v) possible rapid emergence and changes, and (vi) wide-spread implications. Therefore, they should be treated as intricate transdisciplinary patterns of known, partially known, or unknown knowledge and problems (Regeer and Bunders 2003).
- The on-going disciplinary convergence gives floor to systems which come smoothly together not only in the material world (such as integration of atoms, genes, neurons, and memes), but also (and even more effortlessly) in the cyber world (e.g., forming synergies such as molecular informatics, cognitive informatics, neural informatics, brain informatics, and computational informatics).
- The unique discipline of CPSs is a typical example of the dialectic relationship of convergence and divergence. The merge of the disciplines of (i) analogue and digital hardware, (ii) control, reasoning, and application software, (iii) data and knowledge cyberware, and (iv) human brainware, experience, and wisdom is an example of disciplinary convergence and cross-disciplinary knowledge creation, whereas popping up of novel sub-disciplines such as cognitive engineering,

security engineering, system learning, etc. are indicators of the concomitant divergence and sub-disciplinary articulation of knowledge.
- In addition to the omnipresent compositionality, complicatedness of a problematics is also a result of the multifold interplaying natural or created phenomena, dissolved specific problems, and the transdisciplinary knowledge demand, which cannot be observed, measured, and treated individually due to their confounding and inseparable nature. Therefore, problematics are deemed to be beyond the investigational coverage of classical mono- and interdisciplinary research approaches (CohenMiller and Pate 2019).
- The principal challenge for the presented explorative part of the work was finding a rational mechanism for consideration and operationalization of holism in capturing the semantic contents of problematics, as opposed to applying reductionism.
- We presumed and proved that a conceptually and methodologically extended version of the systematic combinatory breakdown (SCB) method, which has initially been proposed for investigation and scoping of naturally existing phenomena, can be applied in investigation and scaling complicated research problematics (Maskaliūnienė and Tatolytė 2023).
- For an insightful investigation and restriction of the scope of complicated research problematics, we propose a procedural framework, which includes four stages of processing things, attributes, relations, and implications, and can be converted into a procedural scenario include both analysis and synthesis actions.
- Computational support of supradisciplinary research is an unsolved problem. The currently used research tools can be invariably applied to specific research tasks, but we miss tools that would support addressing three major challenges. First, organization and procedural management of supradisciplinary programs and projects throughout their complete lifecycle. Second, support the labor intensive and cognitively demanding process of preparing complicated problematics for postdisciplinary systematic studies. Third, creating joint intellectual spaces, maintaining commitment of heterogeneous research communities, and fostering epistemic translations. Such computational tools cannot ignore the social and personal components of doing supradisciplinary research and this is exactly what makes their development and use complicated.

It is obvious that every pioneering undertaking in research opens up uncountable new research opportunities. Follow-up research in this direction is very much needed at least for two reasons: (i) more and more research problematics are being created which beg for urgent, comprehensive, and efficient addressing, and (ii) the proliferating concept of supradisciplinary research needs new methods of research model and research design development. Discussing all possible technical research issues would need multiple papers on its own.

Authors' Contribution: (i) overall: I.H. ~75%, F.-Z. A. E.-B. ~25%, (ii) conceptualization: I.H. ~50%, F.-Z. A. E.-B ~50%, (iii) research report: I.H. ~30%, F.-Z. A. E.-B. ~70%, (iv) paper content: I.H. ~70%, F.-Z. A. E.-B. ~30%, (v) structuring: I.H. ~70%, F.-Z. A. E.-B. ~30%, (vi) references: I.H. ~50%, F.-Z. A. E.-B. ~50%, (vii) imageware: I.H. ~70%, F.-Z. A. E.-B. ~30%, (viii) lay-outing: I.H. ~20%, F.-Z. A. E.-B. ~80%.

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