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Transdisciplinary Shifts in System Paradigm-Driven Disciplines: Mechatronics as an Example

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Abstract: *This paper analyses the multi-faceted progress of system paradigm-driven disciplines (SPDDs) and interprets their drivers, stages, offerings, and impacts of the disciplinary shifts. The basis of the paper is an extensive literature study. Due to the extreme breadth of the field, the authors could not consider all pertinent scholarly domains. Therefore, they placed mechatronics into the focus of their study, collected evidence from this wide-ranging and highly integrative field of engineering, and used it to underpin their reasoning and propositions. After introducing the topic, goals, and approach, the paper includes an interpretational interlude to reduce the conceptual and linguistic Babel associated with modern systems science, particularly information technologies and artificial intelligence in systems. As major drivers behind the observable scholarly changes, the trends of (i) scientific convergence and divergence, (ii) technology integration and synthesis, (iii) paradigmatic nearing of engineered systems, (iv) growing level of cognitive abilities, and (v) multi-faceted socio-ecological embedding have been identified. The authors found that (i) there is a tension between the traditional static view of SPDDs and the dynamically changing systems paradigms, (ii) specific stages can be discerned in the progress of most SPDDs, (iii) the evolution of SPDDs does not stop at reaching a postdisciplinary stage, but continues toward a transdisciplinary stage aiming at the involvement of non-academics, (iv) a novel reasoning model is needed to reason about the fields and knowledge of transdisciplinary SPDDs, and (v) it is not possible to consider all implications of the disciplinary shifts exhaustively due to the diverse functionalities and application fields of systems. The authors propose a reasoning model and suggest using semantic dual-relationships between the identified knowledge spaces to operationalize the model, e.g., to reason about the involvement of specific disciplines necessary to develop next-generation mechatronics, cyber-physical, and artificial intelligence-based problem-solving systems. They conjecture that, in the future, the only feature differentiating these systems will be their functional disposition.*

Keywords: Transdisciplinary shifts, systems science, mechatronics, systems engineering, holistic reasoning model.

1 Introduction

1.1 Domain of Interest

It has become a cliché that we live in a fast-paced world, which poses several challenges even for involved professionals to follow, understand, and process. The accelerated changes cause a lack of transparency and clarity in understanding the progress of system paradigm-driven disciplines (SPDDs). These disciplines may concentrate on monodisciplinary systems (such as a mechanical drive), interdisciplinary systems (such as a microscope), multidisciplinary systems (such as a building), crossdisciplinary systems (such as an advanced mechatronics system), or postdisciplinary systems (such as a cyborg). Other representatives of crossdisciplinary systems are computing paraphernalia, software-integrated systems, complex adaptive systems, embedded automation systems, distributed real-time systems, cyber-physical systems, networked agent-based systems, socio-technical systems, Internet of everything, cyber-physical social systems, and so forth.

The postdisciplinary nature of these systems originates in the epistemological and methodological boundaries that have been blurred or even demolished between the concerned thematic disciplines. In practice, it means that the development of hardware, software, cyberware, and brainware for these systems happens in a holistic framework. In the context of this paper, transdisciplinarity not only means bringing together knowledge from theoretical systems science and systems engineering practice, but also cooperation between academics (of different disciplinary backgrounds) and non-academics (of highly varied professional and societal backgrounds) in the development of systems. The reasoning and propositions of the authors necessarily reflect the uncertainty and constraints of inductive reasoning, i.e., projecting and generalizing the findings related to one or a couple of systems to all systems concerned by SPDDs.

1.2 Objectives and Approach

The informational basis of this paper has been generated by a thematically structured literature study designed with a dual focus. On the one hand, it investigated the past, the current, and the foreseeable near-future trends influencing SPDDs. On the other hand, it focused on the discipline of mechatronics, which is known to be a highly integrative and wide-ranging scholarly field. Nevertheless, the content has been compiled not only from the findings of the extensive literature review but also from the pertinent results of the authors' research work related to mechatronics and cyber-physical systems and their professional experiences. The objective was to foster a deeper understanding of the overall trends and the shifts towards postdisciplinary and transdisciplinary approaches to SPDDs. The underpinning conjectures of the authors have been that (i) the historical evolution of the now well-established SPDDs is similarly patterned, (ii) the disciplines reflect the effects of the epistemological, technological, and methodological trends, (iii) the evolution of their offerings is strongly interrelated with these trends, and (iv) the disciplines share comparable future perspectives and face similar influences.

The authors attempted to derive defendable propositions by contrasting concrete findings. It explains why mechatronics has been selected as a reference (or the exemplary case). Concerning mechatronics, the topics included in the review were: (i) the origins of the overall discipline of mechatronics, (ii) the disciplinary features and designs of classical mechatronics, (iii) the disciplinary features and designs of advanced mechatronics, (iv) an inventory and influence of current mega-trends and the concomitant change factors, and (v) incorporation of artificial intelligence assets in development processes and specific mechatronics systems. Related to the latter, it was observed that different terminologies have been used in scholarly publications, leading to theoretical confusion and conceptual inconsistencies. The authors' goal was to avoid or minimize these by using a consistent terminology for the discussed disciplinary concepts and the forms/levels of equipping systems with cognitive abilities. As a constructive contribution, the authors propose a high-level reasoning model regarding the operational knowledge domains of next-generation mechatronics, cyber-physical, and artificial intelligence-based problem-solving systems. They suggest using the dual semantic relationships between the identified knowledge spaces to operationalize the model to reason about the necessary involvement of specific disciplines and as a highest-level activity blueprint for developing next-generation systems.

1.3 Content of the Paper

The literature study has explored, analyzed, and assessed the drivers, stages, offerings, and implications of the disciplinary progression. The paper is structured according to these aspects. The following section clarifies some fundamental notions concerning the levels of cognitive abilities and the evolution of engineered systems. Using examples from the discipline of mechatronics, Section 3 discusses the trends that eventually manifest as drivers of the paradigmatic shifts in the science and engineering of systems. Section 4 sheds light on the stages of the transdisciplinary shifts and identifies the typical milestones of the evolution of systems and their characteristic offerings (e.g., systems, products, services, and experiences). Section 5 discusses the typical offerings, sorting them into the categories of systems, products, services, and experiences. Section 6 focuses on the observable influences of the discussed changes, considering five important domains, namely (i) engineering mindset, (ii) research approaches, (iii) innovation opportunities, (iv) educational epistemology, and (v) cognitive infrastructure. The last section reflects on the findings, derives some propositions, and indicates future research trajectories.

2 Against the Conceptual and Linguistic Babel

Though this section may seem to be an interlude, it is essential to have a robust terminological foundation. It provides an overview of the fundamental concepts and interprets them in the context of cognitively enhanced engineered systems. The inspiration for including it here is that a conceptual and linguistic Babel prevails in the literature concerning the cognitive ability levels of engineered systems. There seems to be no agreement on the definitions of the growing cognitive abilities of engineered systems. Furthermore, there exists a consistent interpretation of their knowledge utilization levels and processes. The literature is conceptually split in terms of what 'intelligence' eventually means in the context of their implementation and operation of current and next-generation engineered systems. The goal of this section is to reduce confusion and avoid inconsistencies.

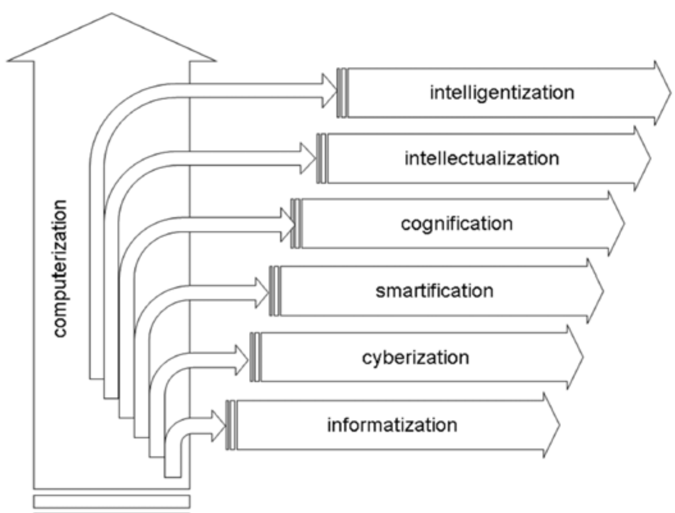

Figure 1: Activities increasing the cognitive abilities of engineered systems.

As shown in Figure 1, the cognitive abilities of engineered systems have been increased in line with the advancement of overall computerization. Using analog, digital, and quantum computers results in a range of syntactic, semantic, and cognitive system abilities. For the sake of this paper, six cognitive ability levels have been considered. In ascending order, they are (i) informatization, (ii) cyberization, (iii) smartification, (iv) cognification, (v) intellectualization, and (vi) intelligentization. These notions describe the activities most frequently used to develop and/or increase cognitive problem-solving abilities and the potential of engineered systems.

2.1 Informatization, Cyberization, and Smartification

Going hand-in-hand with computerization, 'informatization' concerns the conversion of data and information streams into a form that can be stored and processed by digital computers. Informatization is not a new term, but it is at the basis of the information society. It allows the continuous development of digital information and communication technologies to create new opportunities for continuous improvement. As such, it is regarded as the process that makes a geographical area, a sector of the economy, an industrial branch, or a part of society information-based. It concerns adapting organizations, systems, devices, etc., to be operated and controlled by computers, and establishing an increasing flow or diffusion of information and communication technologies throughout a complex techno-econo-social system. Lastly, informatization increases the size and competencies of the needed information labor force. Typical early examples of informatization can be found in manufacturing, logistics, office automation, and the engineered systems used in these productive sectors. The informatization policy also stipulates adopting information technologies to steer and control governments, public institutions, and other entities, and to promote overall socio-economic development within the growing cyberspace.

Used rather frequently, the term 'cyberization' is less transparent. Some researchers refer to it as the whole of computerization, digitalization, datafication, and informatization. In this sense, it means integrating digital systems, activities, and practices into real-life processes and adapting to digital technology, environments, and cultures. Others consider it a specific form of informatization that aims at integrating cybernetic technology into biological organisms to transform them into cyborgs (Zeng and Wu, 2014). It involves enhancing the human brain with cybernetic implants, applying extreme sensors to extend humans' perceptive abilities, and/or replacing human body parts with electromechanical devices (prostheses) to reproduce physical (motor) functionality. Following post-humanist visions and techno-utopian views, other scholars have interpreted cyberization as the effort to create artificial cybernetic organisms (synthetic cyborgs) as human companion species. Such assumptions are strengthened by the new efforts to move toward embodied artificial intelligence agents and realize the framework of the sixth industrial revolution. While a further (technological) merger between humans and machines seems inevitable in the not-too-distant future, this latter form of cyberization is becoming the new inescapable reality of contemporary life. At the same time, it is uncertain if augmenting, surrogate, companion, creative, or reproductive cyborgs (robots) will become real human companions in the next fifty years.

The term 'smartification' refers to the process that enhances traditional systems, devices, products, or processes with advanced technologies. Smartification transforms conventional systems into 'smart systems' capable of logical, adaptive, and predictive behaviors. Smart systems typically comprise several key components, such as physical and software sensors, connectivity modules, data processing units, control algorithms, inferring and reasoning mechanisms, and physical and software actuators. The integration enables these systems to autonomously sense their environment, collect and analyze data, make informed decisions, and perform actions without human intervention. This leads to increased efficiency, adaptability, and user-centric services. The concept of smartification is prevalent across various industries. It supports real-time interaction of systems and devices by triggering events and distributing messages instantly. In the context of products in the manufacturing industry, Schuh et al. (2019) defined smartification as the digital refinement of an existing product by embedding digital technologies and smart services.

2.2 Cognification, Intellectualization, and Intelligentization

Involving knowledge engineering activities, cognification of engineered systems eventually targets sophisticated conscious reasoning ("thinking") about objectives, performance, behavior, or experience of systems. Metaphorically, Kumar et al. (2022) posited that the need for cognification is the outcome of the Fourth Industrial Revolution in which "just-in-time solutions to day-to-day tasks faced by humans arrive on demand, similar to the way electricity flows instantaneously through wires to places of need". Cognification assumes the availability of highly specialized knowledge that can be plugged in depending on the needs of the problem to be solved. The assumed highest level of targeted conscious reasoning is cognizance, also dubbed 'understanding awareness'. However, it must be remarked that there are still several open issues. For instance, the computational implementation of system cognizance (i.e., the phenomenon of understanding awareness) has remained a challenging and unsolved wicked problem. It is widely debated if computer structures can indeed have awareness and understanding in the forms existing with human beings. A less ambitious interpretation of cognification appeared in software engineering. There, it means embedding operational knowledge and reasoning mechanisms in software to achieve an incremental increase in cognitive abilities. The software cognification process involves designing and using knowledge processing modules and applying complex data analytic models that allow mimicking natural cognition in ways that boost the overall performance and effectiveness of engineered systems. Based on experiences concerning the development of generative artificial intelligence mechanisms, cognification is forecasted to make a revolution in the way software is built and self-morphed.

Intellectualization can be best explained by tracing its roots to natural human intellect. It goes in the footsteps of human-like sense-making (intellection). In its original usage, intellectualization refers to the psychological defense mechanism where an individual focuses on facts, logic, and abstract reasoning to avoid being confronted by uncomfortable or distressing emotions. By concentrating solely on intellectual components (i.e., facts, beliefs, and thoughts), people distance themselves from the emotional aspects of a situation, thereby reducing anxiety or stress associated with it. Thus, in common-sense usage, the term refers to the cognitive potential that enables effective human problem-solving using a formalized thought, idea, or conception. It is important to note that balancing logical analysis with emotional awareness is a crucial element of human behavior, while intellectualization can serve only as a coping strategy. In system engineering, intellectualization describes the effort to equip engineered systems with the ability to solve problems, procedural inferring and reasoning, textual and verbal responsiveness, argumentativeness, decision-making, and conclusion drawing. It needs status data, prescriptive/descriptive knowledge, action scenarios and plans, and non-trivial (retrospective, inductive, deductive, and/or abductive) reasoning mechanisms. System intellect is the mental content based on which computational 'grasping' and elaborating a problem is possible in its context. Two complementary but combinable approaches to the intellectualization of engineered systems are (i) preparation for autonomous problem-solving and (ii) empowerment for evolutionary self-management. As a bottom line, the use of the word 'intellectualized' helps avoid the existing conceptual confusions that have been introduced by the terms "intelligent systems" and "intelligent mechatronics" (Roberts, 1998).

The literature is not explicit on the differentiation between non-intelligent and intelligent systems concerning their cognitive abilities, functionalities, performance, or other paradigmatic system features. Some researchers claim that intellectualization eventually leads to so-called 'intelligent systems', i.e., a concept not fully established yet. Cai (2022) argues that intelligent mechatronics systems used in manufacturing are based on the in-depth integration of a new generation of computing, information, communication, and advanced manufacturing technologies. They perform self-perception, self-learning, self-decision-making, self-execution, self-adaptation, etc. Others assume that it needs intelligentization. They argue that the term 'intelligence' means only the computational aspects for the former researchers but fails to consider other (intangible) aspects inseparable from human intelligence that may manifest in four (individual, group, society, and humankind) forms. Artificial intelligence research strives for the 'intelligentization' of systems, well beyond their smartification or intellectualization. However, including artificial intelligence in large-scale, multi-functional engineered systems is not straightforward. It is debated whether building computational intelligence resources into these systems makes them increasingly smarter, and enhancing their computational reasoning capabilities can lead to fully-fledged intelligence. Many researchers believe that it is not possible due to the lack of true (human-like) consciousness (including sentience and qualia) (Crowder et al., 2014). Therefore, some pragmatic approaches reduce the overall intelligentization problem of various engineered systems to the application of intelligent control. To sum it up, on the one hand, there is an irresistible process of convergence of artificial intelligence. On the other hand, a significant knowledge deficit still exists.

3 Drivers of the Disciplinary Shifts

Our literature study explored five mega-trends that concurrently influence the latest developments in SPDDs, in particular, in mechatronics. They gradually transform these from an interdisciplinary manifestation through a multidisciplinary manifestation to a transdisciplinary manifestation. These mega-trends and their essence are as follows:

3.1 Scientific Convergence and Divergence

In the last half-century, the overall structure of the sciences changed due to the strengthening of convergence and divergence mechanisms. Even the 'language of science', the classical crisp (theorem-proofing) mathematics, is going through metamorphoses that give rise to the numerically inferring soft mathematics, AI-geared automated mathematics, and quantum mathematics. The recognized mega-trend behind the observable transformations is the combination of scientific (crossdisciplinary) convergence and divergence. Many experts hypothesized that the advent of these is the result of the progression of the world society (more precisely, the fundamental production and market system of the globalized world). On the highest level, they bring about convergence in terms of economic growth and personal freedom by subjecting all societies to the same forces. This progression also causes divergence in the financial wealth and social power by creating different roles for different communities and entities in the world stratification system. These mega-trends influence not only the scientific disciplines but also apply to and influence technology (Seifert, 2015).

Scientific convergence has both a longitudinal dimension and a transversal dimension. Longitudinal convergence is about blending various forms of dealing with science over time. Empirical science has been extended methodologically by rational approaches (offering formal theoretical modeling) and, later, by computational approaches (offering computational simulation). In the last three decades, it has been enriched by data science methods (offering pattern recognition in massive data sets), propositional reasoning methods (to address challenges of complicated problematics), and the approaches of generative artificial intelligence (offering extensive reasoning over online knowledge repositories). Traversal convergence means the integration of philosophies, knowledge, methods, and values of scientific disciplines across and beyond their boundaries. The formation of postdisciplinary and transdisciplinary science is the result of this. Li (2024) proposed a research framework for exploring, among others, the confinement interaction of diverging science and converging technology. Methodological progression is instrumental to the formation of interdisciplinary, multidisciplinary, postdisciplinary, and transdisciplinary scientific fields, and the integration of techno-scientific knowledge (Maties et al., 2019).

Closely accompanying convergence, scientific divergence has given the floor to the emergence of brand new disciplines such as cognitive engineering, team science, and prompt engineering that are vital in the context of transdisciplinary cognitive systems. There are several other examples of such emergencies, e.g., the branching out of mechatronic cybernetics from the more general engineering cybernetics to deal with the specific issues of control engineering of advanced mechatronic systems and beyond (Liagkou et al., 2021). The internal mechanism of techno-scientific divergence can be explained as the spontaneous appearance and increase of interest in certain parts of interdisciplinary, postdisciplinary, and/or transdisciplinary knowledge that offer the chance for indefinite and non-conclusive evolutionary processes in which the scholarly objectives and professional approaches may become quite dissimilar. Such developments have strongly influenced the existence and evolution of mechatronics. Bringing about new issues and challenges, scientific convergence and divergence will continue and permeate the currently still intact knowledge domains (Siddiqui et al., 2023). Crossdisciplinarity, postdisciplinarity, and transdisciplinarity necessitate an orchestrated adaptation of the research, innovation, and education policies.

3.2 Technology Integration and Synthesis

Like scientific convergence blurred the lines between disciplines, technology integration and synthesis have done the same with system and process technologies. The combination of technologies has both a system-internal aspect and a system-external aspect. To distinguish these, we refer to the system-internal combination of technologies as technology integration, and the unceasing process of system-external combination as technology synthesis. An example of technology integration in current engineered systems is the complementary use of hardware, software, cyberware, and brainware technologies (Freddi, 2009). System-external technology synthesis has two threads. One is interlinking systems modeling technologies such as (i) multi-disciplinary modeling, (ii) multi-level modeling, (iii) interactions modeling, (iv) functional modeling, behavioral modeling and simulation, (v) interactions modeling, (vi) semantic interoperability modeling, (vii) multi-agent modeling, and (viii) environmental effect modeling (Penas et al., 2017). Another thread is about generating new types of postdisciplinary technologies for systems by fusing disciplinary technologies. An emblematic example is the synthesis of bits, atoms, neurons, genes, and memes (BANGM) for next-generation mechatronics and other types of systems that benefit from the convergence of digital, physical, biological, mental, and cultural realms (Horváth and Tavcar, 2021). Many researchers consider this synthesis of technologies as the side stream of the convergence of scientific knowledge. However, this is just partially true. There are also influential conditions, probabilities, dependencies, possibilities, and constraints that originate in the technologies themselves (Maksuti et al., 2023)

The BANGM integration process has started and is becoming more influential and multi-faceted. For instance, integrating information bits with atoms happens in smart materials. Digital data are integrated with atoms in the case of 3D printing devices or are regained from artificial skin. In bioinformatics, software tools extract and analyze genetic data to identify mutations, while bits of information are added to organic substances to design new genes. In the case of brain control of prostheses, electric currents are detected in the human muscle to provide control data. Wang et al. (2020) reported on the neuromorphic engineering of memristive device-based artificial synapses and neurons which are used as building blocks to (i) perform biologically inspired digital/analog computations in memory, (ii) form hardware neural networks for computing acceleration, (iii) enable the implementation of integrated bionic perception and motion systems, and (iv) mimic the human peripheral nervous system for information sensing and processing. To allow precise studies of the operation of the brain neural circuits, optogenetics genetically modifies neurons to be controllable by light (Bansal et al., 2023).

As discussed by Lee et al. (2018), the latest advances in ultrathin electronics, soft materials, and deformable optoelectronics have facilitated the realization of novel processes and device designs that mimic biological vision systems. Bits of information about the neural activities of the brain are extracted by brain-computer interfaces. Integrating bits and genes makes it possible to encode information bits into DNA sequences and store them in an accessible form. Emojis (and emoticons, bitmojis, etc.) as cultural memes express cultural notions, concepts, and/or emotions by patterns of bits as interactions happen in the physical or virtual (cognitive) space. Genes of bioengineered plants for urban greenery are modified to absorb pollutants. Lab-on-a-chip devices are based on integrating atoms, bits, and neurons. Experts foresee the happening of a kind of revolution when all foundational constituents will be combined, for instance, in new post-mechatronics substances (Khan et al., 2023).

3.3 Paradigmatic Nearing of System Paradigm-Driven Disciplines

Current engineered systems are spread over a wide spectrum populated with systems listed in subsection 1.1. Though the names indicate largely different systems, these system paradigms have many common features.

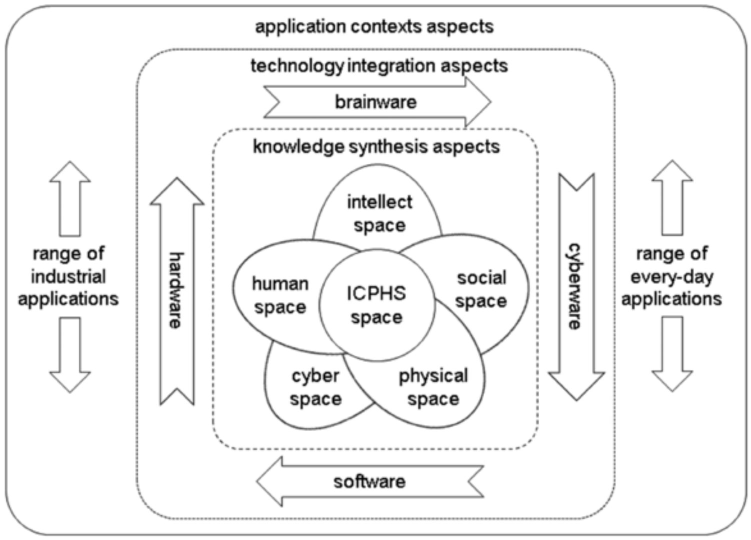

Figure 2: Aspects of transdisciplinary evolution of engineering systems.

For instance, they (i) rely on multi- or transdisciplinary knowledge (i.e., on the ICPSH knowledge space) (Figure 2), (ii) integrate multiple material, energy, information, and knowledge technologies, (iii) are based on the synergetic operation of hardware, software, cyberware, and brainware components, (iv) increasingly share certain general functionalities such as sensing, computing, reasoning, control, and actuating, (v) present growing intellectual capabilities (e.g., inferring, reasoning, decision-making, autonomism, adaptation, evolution), and (vi) are tailored to meet sustainability, safety, security, social, and human requirements. These six aspects indicate the paradigmatic nearing (overlapping) of the abovementioned and other engineered systems. In other words, the ontological, epistemological, technological, functional, and performance features of modern systems show a large overlap under the effects of the mega-trend of unification. It can be assumed that this nearing process will probably go on and become more intense. As a result, it will be challenging to tell fundamental (or discriminative) differences among next-generation engineered systems in the future. What may make a difference between them is their teleology (i.e., for what they have been constructed and with what objective). Their possible differentiating features will probably be (i) the goal of development, (ii) the range of implemented functions, (iii) the physical sizes and embedment, and (iv) the operational environments. As the most important from the viewpoint of manifestation, only functional disposition shall cause intrinsic differences between the genotypes of technologically congruent engineered systems in the future.

For instance, Plateaux et al. (2016) attempted to identify the similarities and differences between advanced mechatronic systems and cyber-physical systems. As commodities, they claimed that both are (i) heterogeneous and cross-domain systems, (ii) functional, multi-domain, and multi-disciplinary integrated systems, (iii) designed for dynamic physical interactions, and (iv) developed by the involvement of many isolated sub-disciplines. They formulated the differences as follows: Advanced mechatronic systems feature (i) fixed configuration (structure), (ii) centralized (control) architecture, (iii) physically integrated in a compact volume, (iv) independence (embedded) and self-reliance (autonomous), and (v) humans are usually considered outside the loop. Cyber-physical systems feature (i) adaptive (configuration) structure, (ii) decentralized (control) organization, (iii) geographically distributed but networked, (iv) inclusion of humans in the loop, (v) functionally and structurally open, (vi) intense internal communication in real-time. In our view, they also differ in that advanced mechatronic systems are usually composable systems, while smart cyber-physical systems are dominantly compositional systems. Despite the theoretically identified differences, the recent implementations of intellectualized mechatronics systems show strong similarities (overlap) with systems developed in the field of smart cyber-physical systems. The paper of Sanghera et al. (2024) gives a demonstrative example of this.

3.4 Growing Level of Cognitive Abilities

In the last two decades, many efforts have been made to include artificial intelligence in mechatronic systems and support their development processes with artificial intelligence-powered tools. As discussed in the preceding section, this must be seen as just one of the possible activities related to digital computing and treated with care. As mentioned above, it is more sensible to formulate the current goal pragmatically as the intellectualization of engineered systems rather than as a fully-fledged intelligentization - though the latter is deemed the engine of moving toward next-generation systems (Gehlot and Rana, 2024). Intelligentization would simultaneously concern the activities of the development processes and the created mechatronics offerings. The former goal can be achieved by involving AI-powered development tools in the system development processes. The latter can be realized either through the intelligentization of the control systems or by incorporating specific computational reasoning learning functionalities. For example, some authors have claimed that this leads to the reinventing of mechatronics and, therefore, proper future directions for mechatronics should be developed (Yan et al., 2020). Others formulated worries concerning the effects of emerging technologies and unified systems concepts on mechatronics (Bradley et al., 2015).

Contrary to the prevailing deficiencies, applying artificial intelligence-based reasoning mechanisms has been the objective since the beginning of the era of advanced mechatronics. As one of the pioneers, Rzevski (2003) proposed using intelligent agents (i.e., software objects capable of communicating with each other and reasoning about received messages. He suggested using the framework of multi-agent technology to support the implementation of intelligent mechatronic systems. Various expert systems have been proposed for a systematic (catalogue-based) composition and configuration of production mechatronics systems. Likewise, rule-based and fuzzy logic-based reasoning mechanisms have been used in the smartification of control mechanisms. Machine learning, neural network-based learning, and deep learning mechanisms have also enabled massive data stream-driven adaptive control (Taylor et al., 2021). Nowadays, many other representative AI tools such as pattern recognition, process planning, computer vision, virtual reality, system diagnosis, image processing, nonlinear control, rule-based reasoning, anthropomorphic robotics simulation, deep reinforcement learning, deep convolutional neural networks, automated reasoning, data mining, process control, and generative chat-boxes are regularly used in mechatronics engineering. Whig et al. (2024) analyzed the transformative impacts of integrating artificial intelligence techniques into mechatronics and their effects on functionality, adaptability, and intelligence of mechatronic systems. Xiong (2021) emphasized the importance of the intelligentization of mechatronics toward increased regional economic growth and benefits.

3.5 Multi-Faceted Natural Embedding

It has been recognized that, independently of their disposition, engineered systems should not form an island, but should be synergistically integrated into the embedding environment. The ultimate goal is to create ecosystems that realize balanced interaction with each other and the physical environment in the largest possible influence area. This endeavor leads to the naturalization of engineering systems. However, this is typically a long process driven by intellectualization and goes through (combined) socialization and personalization. On the other hand, this triggers the gradual paradigmatic evolution of engineered systems and increases their overall disciplinary complexity. This complexity originates not only in the system-level aggregative physical complexity, frequently called structural or functional complexity, but also in the epistemological complexification that concerns the amount and variety of the knowledge needed for a system. The latter complexity impacts the hardware, software, cyberware, and brainware constituents equally well. Epistemological complexity also concerns the human inputted knowledge and the synthetic knowledge created and processed by a system's run-time. Managing these complexities is a hidden factor in ecosystems.

There is a growing need to integrate physical, cyber, cognitive, social, and human aspects of system operations to establish ecosystems. To fulfil the need, two strands of activities should happen concurrently: (i) crossdisciplinary (or transdisciplinary) synthesis of the related bodies of knowledge, and (ii) performance-oriented integration of computational technologies. Beyond satisfying the requirements originating in sustainability, reliability, energy utilization, durability, resiliency, etc., it also assumes functional smartification and intellectualization that concerns (i) the faculties of inferring and reasoning over system knowledge, (ii) the ability to learn, interpret, and behave purposefully, (iii) the aptitude and agency of changing performance objectives, and (iv) the ability to present socially-sensitive and adaptive behavior. A conceptual scheme is shown in Figure 3.

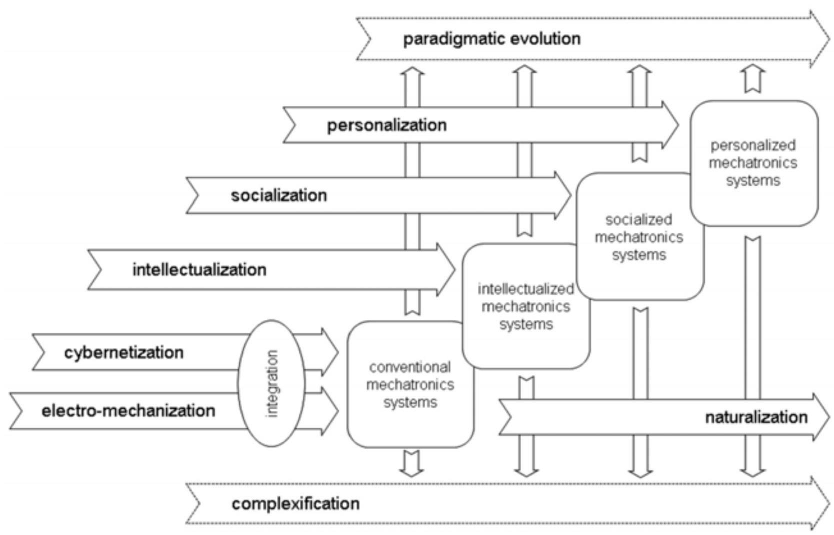

Figure 3: Concurrent trends of changing the system paradigm of mechatronics systems.

Self-acquired problem-solving intellect is becoming a shared asset of functionally intellectualized systems. Their social embedding (or socialization) can be regarded from two perspectives, namely establishing: (i) socialized relationships with various human stakeholders and considering human factors, and (ii).socialized relationships among similar and/or dissimilar engineered systems. Socio-cultural knowledge is typically qualitative, not entirely deterministic, and is difficult to interpret without context. As the current representative approach to socialization, canonical socialization concerns the commonly accepted human relations, patterns, values, symbols, norms, and ethics. Bilaterally processable memes are used to capture these aspects in formal systems. Adaptive appearance and behavioral personalization further extend the operational realms of engineered systems to the emotional, attentive, and apobetic realms. Personalized systems render a human-like behavioral profile and replicate many situated adaptation abilities. Similarly to the case of socialization, it is a significant precondition for proper personalization to have 'insights' in the probable contexts. Many works are driven by the view that the perceived appearance of systems reflects the range of their personalization. In particular, it applies to the varied interactions between humans and humanoid service robots. Current systems use pre-defined character and behavior models (with a large set of rules or machine-learned patterns) for personalized appearance and behavior.

As the above overview shows, the experienced transition has been fueled by multiple drivers that push beyond traditional disciplinary boundaries. The deeper sociological, ecological, cultural, and educational embedding of intellectualized systems needs attention and focused actions in research. The overwhelming majority of the published studies focus on one or closely interrelated issues but fail to cover the whole of this problematics that concerns all next-generation engineered systems.

4 Stages of Transdisciplinary Shifts

Like the development of mechatronic systems engineering, the evolution of SPDDs reflects the progression from traditional, discipline-specific approaches to a more integrated, transdisciplinary epistemology and methodology. This transformation can be delineated into several stages.

4.1 Disciplinary Conjunction Stage

Formation of practically all SPDDs, such as those mentioned in sub-section 1.1, starts with a conjunction stage. In this stage, the first steps toward (i) the formation of a new system paradigm, (ii) probability and possibility-driven knowledge synthesis, and (iii) target-oriented technology integration happen concurrently. After the second half of the 20th century, these evolutionary processes have gained impetus. For instance, the formation of mechatronics as a separate engineering discipline can be traced back to the end of the 1960s. At the beginning of this stage, engineering fields such as mechanical, electrical, and computer engineering operated independently, with minimal interaction or integration. The emergence of this discipline was stimulated by the recognition of the demand for a functional and systemic combination of precision mechanical engineering and wired electronic control. The practical need for feedback-controlled motion formed the basis of the cooperation of mechanical and electronic engineers, boosted the interest in understanding each other's language, and led to the consolidation of the term and concept of mechatronics in an industrial context (Steinbuch, 2016). At the end of the conjunction stage, the system paradigm-driven disciplines establish themselves as interdisciplinary fields of knowledge and engineering.

Let‘s elaborate further using the example of classical mechatronics, which is about designing controlled machines by tightly integrating electronic sensors, actuators, controllers, and signal and data processing into mechanical structures. Typical archetypes include a microprocessor or computer numerically-controlled production machines and collaborative factory robots. Mechatronic designs may be based on different physical principles. Usually, they (i) can sense and actively respond to their operational states, (ii) are regulated by computational algorithms through feedback loops, and (iii) achieve levels of operational precision and behavioral adaptability. The main achievements of classical mechatronics systems engineering were (i) establishing principles of software-based system integration, (ii) moving from analog to digital control, (iii) introducing function-oriented design thinking, (iv) working out solutions for feedback-based and adaptive control, (v) moving towards using digital electronics and microprocessors in mechatronics offerings. After the 1980s, mechatronics cannot be seen as a monolithic discipline anymore. It has lent itself to many branches featuring fairly different objectives, approaches, and offerings. By co-designing platforms, gears, motors, controllers, and software holistically as an integrated whole, mechatronics has started its journey on the bumpy roads of disciplinary evolution.

As reported, the emergence of mechatronics as an interdisciplinary discipline was not a sudden and disruptive phenomenon but a path-seeking attempt and a slow-placed hand-shaking process of the foundational disciplines – something that could be expected based on the prevailing academic reductionism, the sophistication level of technologies, the limited demands for deployment, and the restricted domains of application. It is worth noting that, in the process of its disciplinary formation, Bradley and Dawson (1991) proposed that mechatronics should not be regarded as a separate, self-contained engineering discipline but as a strategy within the overall engineering design process. Instead of a technology-based approach, they suggested adopting an information-based approach to achieve the desired levels of integration in designing mechatronic systems. The strengthening of interdisciplinary systems thinking and embedded digital computation facilitated the synergistic appearance of mechanical engineering, electrical engineering, and operation control in engineered systems (Chavan et al., 2011). Representative tangible examples of this stage of development were electro-mechanical instrumentation of flying, floating, moving, manipulative objects, and household appliances.

4.2 Multidisciplinary Progression Stage

Due to the emergence of new application opportunities, this stage of the evolution of SPDDs is characterized by an intense multi-disciplinary expansion. Though the core remained unchanged, the foundational technologies and problem-solving knowledge have been complemented by application-oriented ones. The progress involved epistemological, methodological, and praxiological augmentation. This has also taken place in advanced mechatronics. Its epistemological augmentation was fueled by multiple disciplines integrated into the core knowledge of classical mechatronics and enhanced its application potential. While the graphical models of classic mechatronics represent it as an interdisciplinary intersection of the foundational disciplines, the conceptual models of advanced mechatronics depict it as a multi-disciplinary integrator of disciplines. Typically, professionals of various disciplines collaborate to achieve a common engineering goal but use their disciplinary knowledge, methodologies, and tools. Specific elements of the epistemological augmentation are (i) application of posterior research knowledge integration, (ii) fostering holistic systems thinking in combination with design thinking, (iii) computer-based simulation and optimization, (iv) benefiting from the resources of the decision theory and complexity theory, (v) involvement of the concepts of economics and sustainability, (vi) striving for automation of everything, and (vii) consideration of exploiting artificial intelligence approaches. Several graphical models have been proposed to identify these disciplines, their interactions, and the extended boundaries of advanced mechatronics (Malisa and Hieger, 2009).

The fact that each discipline maintains its perspective and approach and contributes separately to the actual project makes methodological augmentation peculiar. It happens as driven by offering-oriented activity scenarios and the need for using dedicated disciplinary methods in the various stages of the lifecycle of advanced mechatronics products. An overview of the design models most frequently used in the development of mechatronic products was provided by Buur and Andreasen (1989). They proposed a particular 'model morphology' (and modeling characteristics) as a convenient approach to categorization and a means to invent properties of yet-to-be-existent but necessary models. Praxiological augmentation originates in the necessity of studying intentional (goal-driven) human actions concerning engineered systems. Advanced mechatronics has incorporated such studies of observable human behavior in both the development and the application of such systems. It goes together with (i) changing the working culture (collaboration instead of throwing through the walls), (ii) extensive use of the best development practices, (iii) deploying sophisticated computer-aided tools to achieve optimal efficiency, (iv) applying quality assurance principles, and (v) imposing the rules of ethics and responsibility (Mobarak et al., 2024). Advanced mechatronics sheds light on the necessity of addressing questions related to research methodologies, new materialization technologies, processes, and issues of innovation of offerings, in addition to economic, usability, interaction, and recyclability concerns.

The multidisciplinary-oriented development of SPDDs has blended several academic disciplines and professional specializations, but it also facilitated the appearance of novel application-oriented disciplinary branches. For instance, several new branches of advanced mechatronics have been established after the millennium, involving specific disciplines such as nano-chemistry, molecular engineering, machine vision, optical engineering, humanoid robotics, medical imaging, energy harvesting, sound engineering, etc. These complement the general branches of advanced mechatronics engineering with non-conventional and/or highly specialized application-oriented ones. Without striving for completeness, some representatives of these specific branches are such as (i) opto-mechatronics (Ábrahám, 2001), (ii) hydro-mechatronics (Jian and Zou, 2022), micro-mechatronics (Ishihara et al., 1996), space mechatronics (Kovács et al. 2024), nano-mechatronics (Afonin, 2023), thermonuclear mechatronics (Zoletnik et al., 2024), organic mechatronics (Xie and Huang, 2014), spectacle mechatronics (Fekete and Ábrahám, 2008), cyber-mechatronics (Gheorghe et al., 2017), gadget mechatronics (Anwat et al., 2021), and soft mechatronics (Jain et al., 2020). The diversification process goes on as new bodies of knowledge (such as cognitive, social, cultural, etc.) are included in the development processes and the offerings. One example is the branch of biomechatronics that is still rapidly proliferating (Veltink et al., 2001). Its purpose is to integrate sophisticated electromechanical parts with human beings in a more synergistic manner than that is usually in the form of removable gadgets, such as an exoskeleton.

4.3 Postdisciplinary Intellectualization Stage

We talk about postdisciplinarity when the boundaries of disciplines are broken down, or neglected, and the focus is placed on more general problems and issues of a conglomerate scientific field. Postdisciplinary intellectualization relies on bodies of knowledge integrated independently of their disciplinary origins in the given contexts of SPDDs, focusing on embedded systems, mechatronics systems, and cyber-physical systems. In addition, the cross-pollination of ideas from the interrelated enabling disciplines is pursued to facilitate smart operation and problem-solving. Therefore, postdisciplinary progression cannot be separated from the strengthening need for the intellectualization of engineered systems. In practice, smartification, as an entry-level intellectualization, involves data acquisition by sensing and retrieval, computation and communication, adjustment of control, and actuation of problem-solving functions in repeated operational cycles. It can be directly observed in the case of smartified solutions for control systems (Senthilnathan, 2022). Smartification has facilitated the inclusion of advanced mechatronic systems into Industry 4.0 to enable the implementation of smart manufacturing. For instance, Tomizuka (2002) proposed that a Y2K definition of mechatronics may be “The synergetic integration of physical systems with information technology (IT) and complex decision-making in the design, manufacture, and operation of industrial products and processes.” At this stage of disciplinary evolution, the boundaries between the enabling disciplines become fluid, and holistic frameworks are developed that help transcend the traditional disciplinary perspectives and approaches. As Bradley and Hehenberger (2016) explained, “there has been a shift in emphasis within mechatronics systems from hardware to firmware and software, leading to the introduction of a wide range of consumer products structured around the use of smart devices, many of which remain essentially mechatronic in nature in that they bring together a core of mechanical engineering with increasingly sophisticated electronics and software”.

Besides constructing problem-solving knowledge for mechatronics systems, postdisciplinary intellectualization augments system operation with digital twin (virtual replicas) management, computational reasoning, decision-making, and system-level adaptation. It employs comprehensive mathematical control and system models to grasp complexities, as well as semantic models to integrate knowledge of the pertinent disciplines. Data- and pattern-based reasoning increase both the goal ’awareness’ and the situation ’awareness’ of systems. At the same time, AI methods help problem-solving-oriented reasoning and adaptation of control systems from traditional feedback-based automatic control to reinforcement learning-based adaptive control. Intellectualization using computational intelligence models (i) automates and optimizes system performance, diagnoses issues, and predicts failures, (ii) increases self-diagnostics and self-adaptability by processing environmental and operational data and continuously adjusting system parameters, (iii) improves self-learning and decision-making abilities by cognitive technologies, (iv) enhance natural interaction and real-time communication with system stakeholders and other systems, (v) increase security, safety, resilience, and overall performance, and (vi) optimize resource management, energy efficiency, ecological footprints. This also stimulates socially attuned system behavior. Typically, prognostic systems thinking is used to avoid overlooking critical aspects of complicated system behavior. Effective decision-making is facilitated by dialogue-based interaction between human stakeholders and intellectualized mechatronics systems.

4.4 Transdisciplinary Intelligentization Stage

With the word ‘transdisciplinary’ we refer to a situation where scientific contribution is offered not only by academics but also by non-academics. This creates a new intelligentization opportunity and approach for systems that involves the knowledge and competencies of social stakeholders. In the context of the intelligentization of mechatronics systems, transdisciplinary intelligentization (i) assumes synthesized technological, human, social, and environmental knowledge beyond siloed monodisciplinary knowledge and expertise, (ii) necessitates dedicated problem-solving technologies (enablers) that may be developed on purpose or adapted from artificial intelligence research, and (iii) requires close cooperation and knowledge circulation between systems engineers and societal stakeholders. The emerging field of cognitive systems design/engineering is supposed to address these issues simultaneously and to become a key player in transdisciplinary intelligentization. This opposes the frequently stated views that transdisciplinary intelligentization (i) is a pure scientific challenge that originates in complexities and heterogeneities, (ii) depends only on the availability of applicable artificial intelligence technologies, and (iii) will be established based on the commons created by artificial narrow, generative, embedded, creative, and/or general intelligence complemented with synthetic systems intelligence. On the other hand, having the abovementioned facts as three resources creates a self-amplifying intelligentization process towards autonomous operation and problem-solving.

The above is strongly 'seasoned' by the still existing controversy over how to define intelligence, human intelligence, and, in particular, artificial intelligence or synthetic intelligence. Should the latter be supposed to be a fully-fledged reproduction of human intelligence relying on consciousness and unconsciousness in the foundational processes, or just an embodied agent intelligence that avoids or prevents innate phenomenal complexity but provides support in challenging combined motor, perceptive, and cognitive tasks? We must not forget that the compositional nature of human personal intelligence is also the basis of the intelligence of groups, the intelligence of societies, and the intelligence of humankind. Should we think of the transdisciplinary intelligentization stage of engineered systems with or without the assumption of replicated human consciousness (awareness and responsiveness to something), qualia (content and nature of subjective experience), sentience (ability to experience feelings and sensations), and thinking (intuitively considering and reasoning about something)?

Reproducing collective human-like intelligence would assume the reproduction of these fundamentals. Despite the accelerating development of AI technology and the endeavor to create quantum-conscious artificial intelligence, these are still open issues. Current research seems to bypass these. What currently happens in the context of the intelligentization of mechatronics systems is the development of distinct computational algorithms and/or complex computational mechanisms to complete data processing more effectively than human beings can do due to the intrinsic memory and association capabilities of the human brain (Hashemi and Dowlatshahi, 2023). Apart from the prevailing knowledge deficiency and technological difficulties of reproducing any counterpart of human intelligence, creating human companion systems for out-of-laboratory use is also an open issue. Thus, essential questions of the transdisciplinary intelligentization stage are if it is possible to capture levels of human collective intelligence and if it is needed and can be useful to create non-biological or semi-biological humans (synthetic cyborgs) that can practice freedom in respectable actions and take all responsibility for their actions and the consequences. These are not only scientific and technological issues related to SPDDs and intelligent engineered systems, but also deeply-going philosophical and ethical questions. On the other hand, intellectualized mechatronics systems can already provide evidence for the benefits of solving tasks that cannot be addressed by natural human capabilities or with the same efficiency, no matter if they exist in the physical, perceptive, or cognitive realms.

5 Offerings of System Paradigm-Driven Disciplines

5.1 System-Type Offerings

SPDDs focus on creating technologically heterogeneous, application-oriented hybrid systems. For instance, the initial goal of mechatronics was to support industrial processes, but facilitating everyday processes has also emerged as a new opportunity. Specific instances of system-type offerings of classical mechatronics were (i) partially automated industrial production equipment (CNC machine tools, measuring devices, automated warehouses), (ii) robotic equipment and manipulators (e.g., assembling, measuring, welding, painting, precision, pick-and-place robots, ATMs) and (iii) analog-controlled household appliances (e.g., washing, cooking, vacuum cleaning, cooling machines, microwave ovens), (iv) assistive automotive sub-systems (ABS, steering. airbag, and cruise control), (v) customer durables (e.g., photo cameras, video recorders, cassette players, printers/scanners, sport accessories, analog synthesizers, electronic wristwatches, medical diagnostic devices), (vi) installed transportation equipment (e.g., lifts, conveyors, escalators, traffic controls), (vii) controls systems (e.g., relay-based switching, PID, PLC, digital feedback control, autopilots). The operation of such systems (i) blends material, energy, and information flows, (ii) can be conceptually modeled as finite-state symbolic systems (such as finite-state machines), (iii) is regulated by passive or active digital control, and (iv) happens dominantly in the physical realm where it can be described by infinite-state analytic systems (such as differential equations).

Advanced mechatronics engineering has introduced novel types of systems that are sorted typically into the following classes: (i) data-driven systems, (ii) smartified support systems, (iii) socialized systems, (iv) personalized systems, and (v) multi-feature systems. Data-driven systems (i) are equipped with physical and software sensors to monitor continuously, (ii) implement quasi-real-time data acquisition and processing, and (iii) their control system adjusts the operation of the hardware and software components accordingly. Smart agent-like systems are equipped with some form of computational reasoning to execute tasks and enhance their functionality, adaptability, and autonomy in context. Socialized mechatronics systems, such as cobots, are designed to collaboratively and socially sensitively interact with humans, other machines, or their embedding environment. Multi-feature systems show various combinations of the aforementioned operational features, but may manifest in more complex forms. Personalized mechatronics systems, like humanoid robots, consist of hardware and software designed and customized according to personal morphology, outlook, and actions. The fact is that the last three classes represent the transition from advanced systems to intellectualized mechatronics systems. The concept of a system of mechatronics systems is receiving growing interest as an integrated arrangement of multiple component systems that interact with one another to perform complex, reducible tasks, like a fleet of drones. Research has addressed several engineering issues (e.g., control, communication, interaction, and timing).

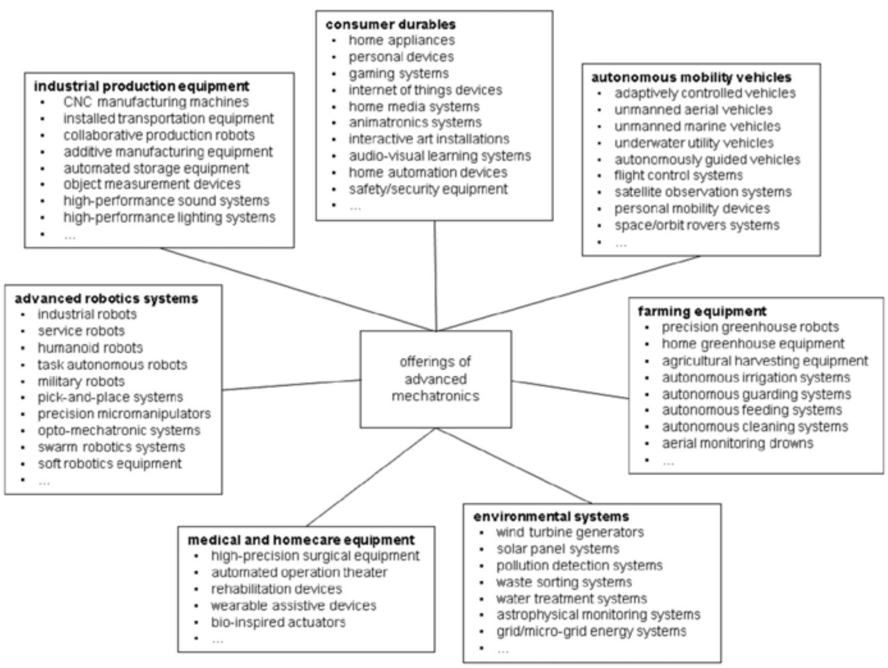

Figure 4: Categories (archetypes) of the main offerings of advanced mechatronics engineering.

5.2 Product Type Offerings

While classical mechatronics concentrated on mechanically architected machines and devices, advanced mechatronics opened up for software-integrated, sophisticatedly controlled systems, equipment, machines, appliances, devices, kits, and utilities (Janschek, 2011). It has resulted in extreme diversification of product type offerings and the dominance of offerings for non-industrial use (Figure 4). Extending the categories of the electronics constituents identified by Braga (2002), the functional building blocks of these have been (i) mechanical structural components, (ii) controls of motion characteristics, (iii) controls of energy and information flows, (iv) time-dependent semi-conductor controls, (v) half-bridges and full-bridges, (vi) thyristors-based power controls, (vii) solenoids, servos, and shape memory actuators, (viii) stepper motors, (ix) on-off sensors, (x) physical quantity sensors, (xi) hydraulic effectors and regulators, (xii) pneumatic effectors and regulators, (xiii) light, sound and temperature effectors and regulators, (xiv) computer interfaces, (xv) wireless transmitters, (xvi) human interfaces and handlers, (xvii) embedded software components, (xviii) computational learning mechanisms, and (xix) portable/renewable power supplies. A remarkable innovation was the introduction of 'embedded systems' to realize software-driven functionalities (Bradley and Russell, 2010). The application-oriented combination of these building blocks allows the implementation of a broad range of product-type offerings.

The growing opportunity of integrating hardware, software, and cyberware technologies stimulated the evolution of, for instance, humanoid robots that allow interaction with tools made for humans and the embedding environments. This category of robots decomposes to (i) androids (designed to act like a human), (ii) geminoids (designed to change face like a human by moving their shoulders, head, eyes, and mouth), (iii) cyborgs (designed to mimic the human shape, morphology, motions, actions, behaviors, and communication), and (iv) animatronics (designed to replicate human abilities visually in 2D or 3D virtual manikins). Each of them has many instances in uncountable forms and applications. The idea of a 'cybernetic organism' (cyborg) as a product has been pushed by the reality that millions of people need biological support or extensions (Kline, 2009). Over the years, the striving for cyborg enhancement technologies has been complemented by efforts to create genuine human replicas that morphologically, behaviorally, and cognitively reproduce humans with impressively high fidelity. The brain, the senses, and the limbs were enhanced by implants that facilitated a wide range of functions. Barfield and Williams (2017) provided an extensive overview of the cyborg enhancement technologies that bring mechatronics, computer, and cybernetics technologies into synergy. Beyond science and technology, cyborgs extend to morals, values, and ethics (Warwick, 2003) and, therefore, require unprecedented proactive regulation and responsible development. (Ibanez, 2023).

5.3 Service Type Offerings

In the last three decades, the sustainability issues related to creating new economic assets in the form of mass-produced artifacts have led to the concept of the service economy (Shek et al., 2015). As a technologically and socially sensitive economic system, the service economy guides economic activities toward the production and delivery of services rather than toward offering materialized systems or products. SPDDs have been seen as enablers of achieving this overall objective. Though the servicing's object can be hardware and software, recently established SPDDs typically support information-based servicing. Just after the turning of the millennium, Tien and Berg (2003) interpreted service systems engineering as a multidisciplinary field and discussed several system-related issues and methods in the context of providing services by systems. There is a wide field of applications where information-based servicing leads to both social benefits and economic advantages, such as healthcare, entertainment, finance, education, marketing, hospitality, governance, security, and well-being. The emergence of ubiquitous technologies facilitated servitization and opened new perspectives for servicing (Gerritsen and Horváth, 2010).

Producing service-type offerings by SPDDs needs the extension of their knowledge platform and the transformation of their traditional system-centered and product-centered business models into service-oriented models. Examples are hardware-as-a-service (HaaS) (where infrastructure, equipment, robots, appliances, etc., are not sold, but are provided as a service) and software-as-a-service (SaaS). Kuru and Yetgin (2019) discussed the concept of service-oriented cyber-physical advanced mechatronics systems to create remarkably intelligent autonomous products by forging effective sensing, self-learning, Wisdom as a Service, Information as a Service, precise decision making, and actuation using effective location-independent monitoring, control, and management techniques. Implementation of service robots and designing services are hot issues in many SPDSs. Recently, Li et al. (2022) provided an overview of many design issues related to preparing such systems for servicing in indoor environments.

5.4 Experience Type Offerings

Experience economy was introduced as the next emerging wave of economic history more than 30 years ago (Pine and Gilmore, 2013). Experience-oriented thinking resulted in a conceptual platform for researchers and producers pursuing new value-creating activities. Stakeholder, customer, and user experience have been understood as the phenomenon (e.g., satisfaction, excitement, pleasure, and curiosity) delivered by a particular industrial offering (system, product, or service). For this reason, it is often regarded as a parafunction that complements the transformative and informative functions of engineered systems. Certain researchers refer to the experience as a complementary or premeditated offering. Experience is much more intangible than the other offerings, but its apobetic effects can be the same or even higher. The specific levels of complexification, intellectualization, socialization, personalization, and naturalization of engineered systems largely influence the experiences. On the other hand, it has become mandatory for SPDDs to deal with it and design experiences according to concrete demands and presumed renderings.

As a term, ‘system experience’ refers to the overall impression of the stakeholders concerning the operation, interaction, usability, and comprehensibility of a system as a whole (Savioja et al., 2014). System experience is not only momentary or occasional, but also enduring, starting at the installation, through the operation, adaptation, and evolution, to the end of the life cycle of a system. This interpretation has particular importance in the case of everyday systems. Notwithstanding, the overall phenomenon and nature of experience cannot be ignored in the case of industrial systems. That is why stakeholder-oriented and/or experience-centered system development has emerged as a new strategy, among others, in the case of mechatronics systems. Systems designers and engineers work on new methodologies that allow hyper-personalized experiences for stakeholders to address their changing behaviors and expectations. These trigger a new shift towards the experience economy.

6 Implications of the Disciplinary Shifts

6.1 Implications on the Engineering Mindset

The recent developments in SPDDs, in particular, the move towards crossdisciplinary, postdisciplinary, and transdisciplinary formations, and the appearance of knowledge-intensive problem-solving systems, challenge our currently existing ontological and conceptual models. Various graphical schemes have been proposed to describe the range and relationships of disciplinary domains enframed in SPDDs. The literature presents many of them concerning the classical and advanced mechatronics, but also for the realm of first-generation and second-generation cyber-physical systems. However, these schemes include a high level of generality since they do not consider the dependencies of the involved knowledge domains on the specific applications (for instance, the branches of advanced mechatronics). Consequently, they reflect some levels of indeterminism and incidentalness. The questioned graphical schemes offer static representations. They capture only the nature of disciplines and the relationships of the knowledge domains deemed pertinent according to a given interpretation or for a particular application domain. However, with a view to postdisciplinarity, the conveyed knowledge is becoming more important than the source disciplines that produced it.

Only applying the reductionist view is in conflict with the prevalent need to consider complexities in their entirety. Assuming composable systems and forgetting about establishing compositional knowledge needed to address technologically- and/or socially-induced problematics is another deficiency. These require more than just the knowledge of merely technology-oriented disciplines. Including cognitive, social, human, sustainability and other bodies of knowledge integrally is indispensable. It goes so far as to conceive the postdisciplinary manifestation of next-generation engineered systems. The traditional conceptual schemes must be redesigned when fundamental disciplinary and technological changes happen. Therefore, the new models are supposed to be not only more comprehensive but also more resilient to changes. The mentioned issues are not ignorable reasons why we need a new mindset to devise a novel conceptual framework.

On the other hand, dealing explicitly with the interrelated bodies of knowledge involved in the various branches of crossdisciplinary, postdisciplinary, and transdisciplinary SPDDs seems to be a more favorable approach. The advantage of this approach has been recognized not only from the perspective of thematic description of SPDDs, but also from the aspect of conceptually framing and streaming knowledge towards specific intellectualized application systems. These, however, need a new mental model that can serve as the basis of a formal reasoning model. In practice, it means replacing the traditional discipline-inclusion models with a novel knowledge fusion framework (and graphical model).

Our hypothesis has been that the realization and operation of next-generation systems are underpinned by the physical, cyber, human, social, and intellectual knowledge spaces. They are necessary and sufficient to define their manifestation, operation, behavior, and relations. Therefore, at dealing with and reasoning about the disciplinary contents of next-generation engineered systems, it is more practical to start from the knowledge spaces than to deal with disciplines. It also facilitates a balanced comprehension of the engineering aspects and the possible offerings of postdisciplinary SPDDs, like intellectualized mechatronics.

The bodies of knowledge delivered by postdisciplinary SPDDs have to be sufficient for designing intellectualized, socialized, personalized, and sustainable (next-generation) systems. In a design process, chunks of knowledge are picked up in these knowledge spaces and synthesized into a feasible engineering solution. However, this latter cannot be done independently of the purpose, functionality, architecture, characteristics, and application of the concerned system. Therefore, while the foundational knowledge spaces remain constant, disciplines that need to be involved to operationalize the individual knowledge spaces may vary by case. In other words, the disciplines will be the variables, and the actual knowledge chunks and methods delivered by them will be the enablers of the creative process. That is to say, this new conceptual model makes the outside inside to provide comprehensiveness and resilience. The consideration of the disciplines depends on the relevance of the bodies of knowledge for a particular objective and in a given context of system development.

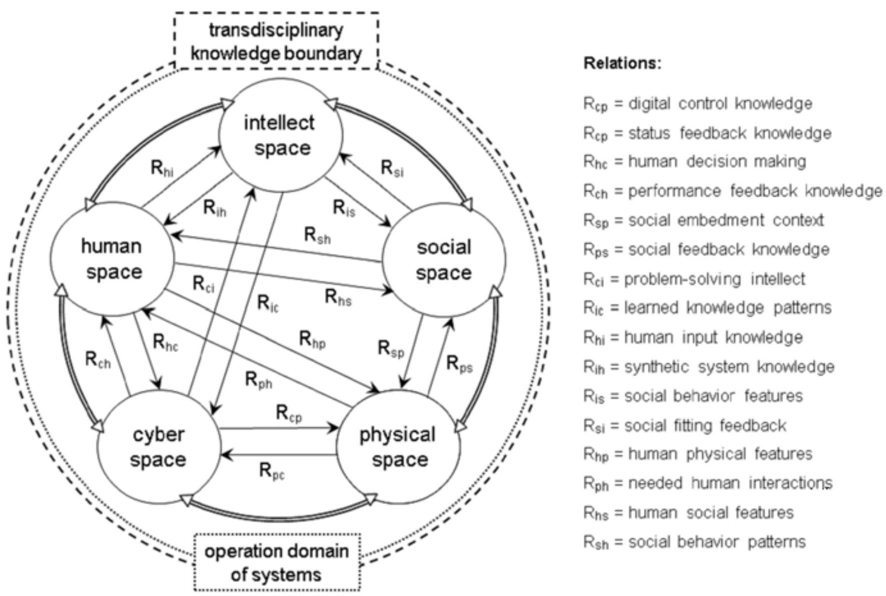

Figure 5: The knowledge spaces and the semantic relations.

The above-discussed conceptualization (i) is in concert with the different branches of intellectualized mechatronics engineering, (ii) supports the development of both composable and compositional systems,

(iii) implies top-down reasoning from epistemological and methodological perspectives, and (iv) triggers the inception of new system and solution ideas. Figure 5 graphically shows the above-identified knowledge spaces that can be used equally well to identify the enabling disciplinary contents for SPDDs, such as intellectualized mechatronics, and specify necessary mappings of the knowledge spaces towards some intended offerings. Figure 5 also indicates the general and pair-wise semantic relations between the involved knowledge spaces. While the spaces refer to bodies of knowledge, the relations indicate specific knowledge combinations and exchanges for the sake of a design objective.

It is important to note that there are no direct semantic relationships assumed between the intellectual space and the physical space due to the consideration of the philosophical dichotomy of mind and matter. At the same time, they are indirectly connected either through the intellect-human-cyber-physical chain or via the intellect-social-physical chain. These can also be seen as patterns of cooperation between humans and systems. It is also worth mentioning that the conceptual framework is not deterministic because the actual contents of the knowledge spaces and their levels of synergism are not deterministic. The postdisciplinary scientific territory of SPDDs, like intellectualized mechatronics, can be variously 'covered" by enabling disciplines in line with the convergence and divergence trends in time. Such an update causes changes both in the bodies of knowledge actually residing in the knowledge spaces and the actualization of the pair-wise knowledge construction relations. Eventually, this conceptual framework does not lose its validity in the case of transdisciplinary SPDDs. The named knowledge spaces can include both tested scientific knowledge explored by academics and intuitive, heuristic, and experiential knowledge of industrial and social stakeholders. Eventually, this determines the knowledge available and usable in system development.

As mirrored by the proposed conceptual framework, the way of thinking has been underpinned and supported by several contemporary publications that (i) have reported on recent boundary-stretching and road-paving innovations in mechatronics, (ii) noted the appearance of novel disciplinary concerns such as cloud computing, blockchain, problem-solving, sensor fusion, swarm robotics, knowledge sharing, etc., (iii) foresee the proliferation of (so-called) intelligent control, (iv) recognized the unpredictable influence of generative artificial intelligence on the knowledge-retrieval and constructive sub-processes of intellectualized mechatronics, and (v) emphasized the importance of moving towards socially adaptive and human-friendly mechatronics. Also, it must be considered that some disciplinary fields may become obsolete in line with the evolutionary trends of the science of mechatronics. At the same time, disciplines may emerge to play a crucial role in mechatronics systems engineering. The proposed framework has been considered as a high-level guide for conceptualization and designing systems based on a context-dependent specification of the intrinsic relations among the knowledge spaces. The tests of the framework as a means of characterizing various manifestations and facilitating their conceptualization of novel intellectualized mechatronics systems are ongoing.

6.2 Impacts on Research

Doing research in intellectualized systems requires simultaneous consideration of novel epistemological concepts and novel methodological constructs. There are two reasons why novel epistemological concepts should be considered. First, the development of intellectualized mechatronics systems goes together with the emergence of technologically, industrially, socially, and culturally created problematics, in addition to the prevailing and emerging phenomena (Horváth and Erden, 2024). Second, both the development and operation of these systems need transdisciplinary knowledge as an important complement to monodisciplinary knowledge (Hernandez-Aguilar et al., 2020). The fact is that the engineering of intellectualized systems offers uncountable new topics for front-end transdisciplinary research. Learning and using novel methodological constructs are needed because the traditional approaches may be inappropriate for handling complex problematics, and postdisciplinary and transdisciplinary system knowledge issues.

Figure 6 shows the logical framework of the supradisciplinary organization of research for intellectualized systems. The framework includes three branches of activities having different foci and logic. The first one concentrates on processing the research problematics. It starts from vaguely circumscribed overall problematics and ends up with a formal (structured) rendering of definitive (scoped) research problematics

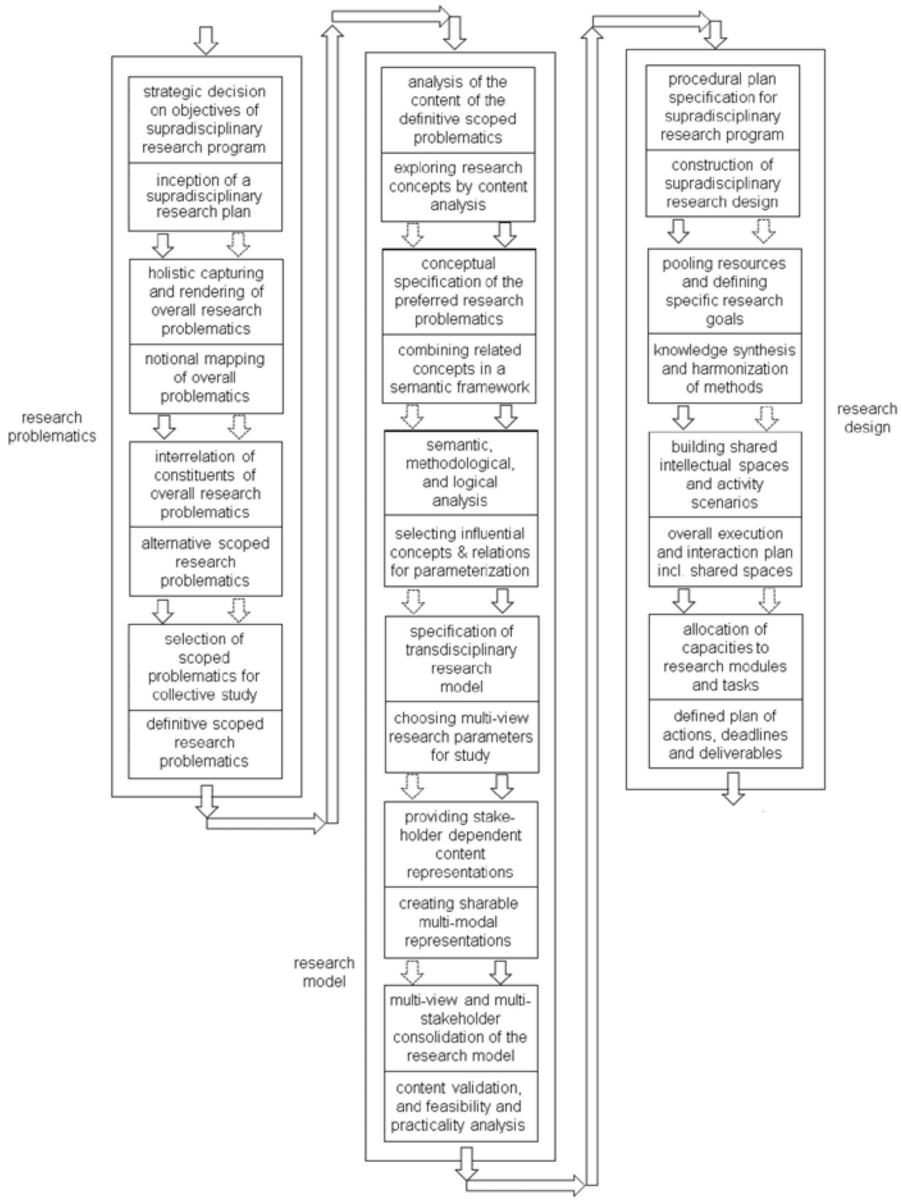

Figure 6: Overall preparation procedure of transdisciplinary research.

(Horváth and Abou Eddahab-Burke, 2024). The second branch of activities transforms the definitive research problematics into a transdisciplinary research model. The model identifies not only research concepts and research variables but also research constructs that need transdisciplinary investigations (Horváth, 2025). The third branch focuses on a supradisciplinary research design that provides a procedural scenario of the disciplinary research activities and supports the allocation and building of research resources. Though set to the top of activity lists, cognitive support of research activities using artificial intelligence is still premature (Xu et al., 2022).

Epistemological and methodological issues of primary importance are as follows: (i) crossdisciplinary and postdisciplinary knowledge generation needs structured collaborative scenarios to involve the investigators of the various disciplinary fields; (ii) transdisciplinary knowledge generation assumes collectives comprising both academic as well as public (social, governmental, administrative, individual, etc. stakeholders; (iii) supradisciplinary organization of research may also blend monodisciplinary, interdisciplinary, and multidisciplinary research activities, methods, and knowledge; (iv) building shared intellectual spaces is beneficial to increase mutual understanding, profiting from best practices, and synthesize, record, share, and consolidate transdisciplinary knowledge; (v) supradisciplinary organization of research allows focusing on problematics that feature both scientific importance and social significance; (vi) in the case of intellectualized mechatronics systems and cyber-physical systems, dedicated frameworks and practical approaches enable the exploitation of synthetic systems knowledge produced by them; (vii) development and propagation of the ethical principles and legal rules of responsible development and exploitation of artificial intelligence must accompany all explorative and constructive research activities; and (viii) mastering the supervision of scientific knowledge generation, for instance, by constructive AI tools and intellectualized mechatronics systems, are mandatory not only for principal investigators.

Among the several recognized challenges of conducting postdisciplinary and transdisciplinary systems research are (i) the current structures of research institutions, (ii) harmonization of the goals of multiple scholarly partners as well as of social stakeholders, (iii) overcoming the cognitive limits and professional constraints of knowledge in-take, (iv) balancing the human attitudinal differences concerning working in mixed teams, and (v) reducing the uncertainties of scientific decision-making processes. Some of these have been extensively studied in the literature, while others are still under-attended emerging issues in specific research contexts. The theory and methodology of collaborative research initiatives have stimulated the emergence of supradisciplinary research strategies and team/crowd science studies. They concentrate on promoting research programs and projects across traditional boundaries and working out new stakeholder models for the involvement of governmental entities, social stakeholders, funding agencies, and industry partners in joint thinking and acting frameworks, beyond the collaboration of researchers.

Like artificial intelligence resources, intellectualized engineered systems can also contribute to moving from the dominantly mono-disciplinary Mode 1 science, through the postdisciplinary and transdisciplinary Mode 2 science, to the formation of Mode 3 science (Yu et al., 2024). In the latter, though there are both stunning results and ambitious imaginations of using artificial intelligence, the long-term true possibilities and probabilities cannot be forecasted yet, though some policies have already been proposed (Kim, 2017). The realistic goals of using AI technologies as enablers in scholarly research and science building may be threefold: (i) aiding, (ii) motivation, and (iii) discovery. Aiding means the support or execution of research activities by selected AI technologies. The activities can be such as automated literature surveys and evaluation of complex data structures, which were previously done by human investigators using conventional software tools. Motivation is a unique disposition of AI to pose novel research questions, conjectures, and hypotheses as practiced by humans working in teams, e.g., extrapolating from the outcomes of completed projects. Discovery involves finding, describing, and explaining unknowns by AI technologies, e.g., heuristic speculation. Should these three abilities concurrently exist and work in symbiosis, they may facilitate the manifestation of Mode 3 science, at least in our view. Carayannis and Cambell (2007) identified five key elements of the Mode 3 scientific knowledge production approach: (i) knowledge-based and innovation-based democracy, (ii) democracy-style governance for integrating various modes of knowledge and innovation, (iii) balancing and integrating pluralistic modes of knowledge, (iv)'democratic approach to decision-making by emphasizing social accountability, and (v) learning from 'forward-looking, feedback-driven' as well as future-centric knowledge exchange through innovation networks. Studies show that even the perceptions and opinions of AI experts are split on the possibility and the probability of artificial intelligence-based knowledge explorations. On the other hand, they emphasize the importance of considering the societal implications, ethical responsibilities, balancing innovation with education, and the interest of the wider public in participation.

6.3 Impacts on Innovation

The dual goals of innovation are fulfilling latent customer demands and maintaining the competitive potential of companies. These also apply to SPDDs. The former implies innovation in the offerings, the latter in the creative processes. As general activities, innovation of transdisciplinary system engineering offerings needs (i) anticipation of novel system features by projecting out from existing and/or expected technological affordances, (ii) converting the indicators of the trends of social demands into a broadly based ideation, (iii) consideration of the highest-level of changeability and adaptability possibilities, and (iv) navigating the ripple effects potentially caused by the introduced technical changes. As human attitudes, it assumes dissatisfaction, intuitiveness, and ingenuity. These are indispensable for recognizing problems, out-of-the-box thinking, and envisaging solutions for problems. It also needs pragmatism, i.e., thinking purposefully and without getting confused with constantly growing complexity, increased heterogeneity, changing conditions, hidden paradoxes, intrinsic ambiguity, and aggregating misinformation.

It has been learned from the appearance of intellectualized mechatronics systems that it entails different views on system innovation and development (Habib, 2007). Though human ingenuity is the key enabler of innovative offerings and processes, artificial intelligence is also expected to become an innovation enabler. In principle, it can facilitate mechatronics innovation by making offerings smarter and by increasing the efficiency of creative processes. On the other hand, its operationalization in the mentioned contexts requires brand-new approaches beyond model-based design. Though many researchers have emphasized the (assumed) power of generative artificial intelligence in radical innovation, as well as its significant potential to augment human creativity in innovation processes as a collaborative partner (Sedkaoui and Benaichouba, 2024), current AI technologies are not such strong facilitators.

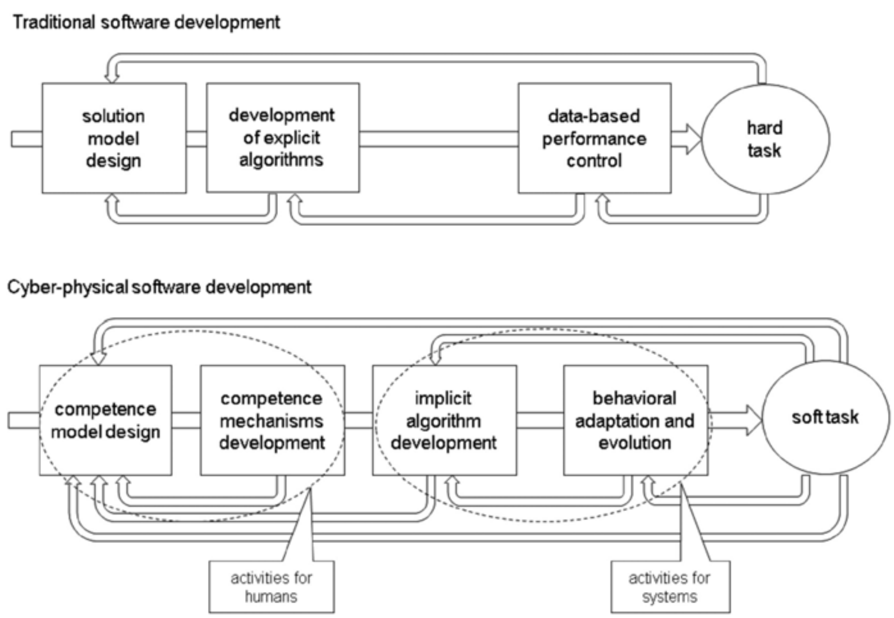

Figure 7: Traditional and hybrid (extended with self-management) system development doctrines from the perspective of software.

Even the latest generative AI tools extended with limited scope reasoning are not able to support genuine innovation because of their limitation in: (i) understanding the real-world context of innovation possibilities and limitations, (ii) establishing a bridge between focused (concretized) needs and undocumented (physical) functionality, (iii) generating never-documented meaningful and feasible combination of technologies, (iv) acting purposefully, creatively, and concurrently in the conceptual, virtual, and physical domains. Some publications provide evidence and explanations about why it is facing heavy limitations on its current level of development. Another proliferating new idea is self-innovation by intellectualized mechatronics systems. This is triggered by the growing self-managing capabilities of intellectualized mechatronics systems that complement human developmental actions (Figure 7). Self-management may range from self-tuning through self-adaptation and self-evolution to self-reproduction. These make changing the system models and the control models possible at different scales. Self-adaptation and self-evolution assume aggregation of data (information) about the state and performance of the system, and autonomous planning and interchanges as needed to enhance operation.

6.4 Impacts on Education

The 21st-century academic education, in particular, of systems science and engineering education, is influenced by many factors. A part of this is internal (that is, rooted in the discipline of education), whereas others are pure external factors that are consequences of various high-level trends and situations. Figure 8 shows a representative set of the internal and external factors. From a teleological perspective, systems science and engineering education is supposed to address both global challenges and local demands. In the former context, the effects of the explosion of technological knowledge, the irresistible proliferation of artificial narrow intelligence, and the complexification and heterogeneity of up-to-date systems had to be considered. In the latter context, adaptation to dynamic changes has been an issue. Including artificial intelligence methods and tools in engineering education proved challenging in both contexts and requires new approaches to designing mainstream programs and specialization courses.

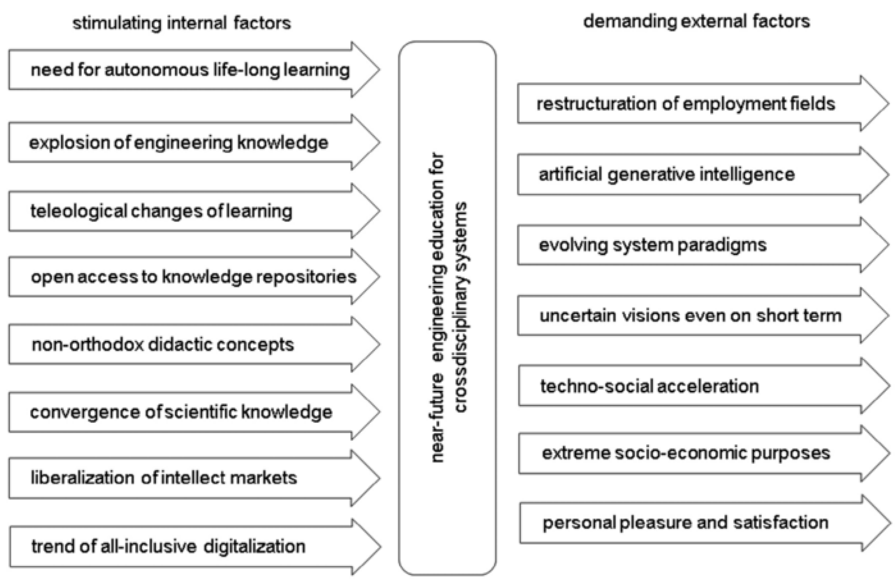

Figure 8: Factors influencing SPDDS education.

Before the millennium, education in SPDDs followed the overall disciplinary and technological advancement in industrially developed countries (Sahoo et al., 2021). Typically, it has progressed through adapting and combining the engineering courses of existing engineering programs. For instance, a standard method of introducing new dedicated degree programs in mechatronics was putting concerned disciplinary courses into a crossdisciplinary framework (Grimheden and Hanson, 2005). In undergraduate and graduate advanced mechatronics and robotics programs, theory and practice have been combined to equip learners with multi-disciplinary knowledge and prepare them to cope with simplified practical tasks. However, the proliferation of intellectualization raised the need for new fundamental approaches to postdisciplinary and transdisciplinary learning and the development of innovation competencies. It triggered the quest for synergistic epistemological and methodological approaches.

Systems education is also influenced by local factors, such as (i) regional educational goals and policies, (ii) institutional qualities and accreditation levels (iii) specific needs of local industry and infrastructure, and (iv) regional industry-academia relations and economic opportunities. Taking these factors into consideration, new principles need to be considered, for instance: (i) the primary objective is fostering epistemological synergy by using proper methodological approaches, (ii) providing balanced attention to the various bodies of knowledge belonging to the intellect. cyber, physical, human, and social spaces, (iii) achieving synergy in the educational practice by a goal-oriented composition of lectures and practices, (iv) extensively considering the specificities of availing knowledge and approaches for pluridisciplinary activities, (v) bringing hardware, software, cyberware, and mindware education into synergy, and (vi) achieving a much higher level of holism than usual in current engineering education.

There is a growing recognition of the need for educational frameworks that promote integrative thinking, crossdisciplinary learning, and human-centeredness. Fait et al. (2020) suggested using the constructivist approach in contemporary mechatronics education. As a counterpart of the bottom-up educational strategy, which follows the principle of reductionism, the idea of the top-down teaching of cyber-physical systems has also been considered. This holistic approach presents the system as a whole and explains its constituents from a systems engineering perspective. The main element of this teaching approach are: (i) explaining and demonstrating typical system phenotypes and prototypes, (ii) presentation and discussion of the underpinning system paradigms, frameworks, and models, (iii) introduction of the ontological, architectural, functional, and elements of representative systems, (iv) introduction and investigation of the supporting concepts, technologies, and methodologies, and (v) delivery of contextualized bodies of disciplinary knowledge needed for system design and/or implementation. This approach also entails the need for interlinking the knowledge chunks related to the parts of the life-cycle: (i) system and human problem-solving knowledge, (ii) begin-of-life knowledge, (iii) design knowledge, (iv) engineering knowledge, (v) middle-of-life knowledge, (vi) synthesized system knowledge, and (vii) end-of-life knowledge.

6.5 Impacts on Cognitive Infrastructure

Cognitive infrastructure has been conceptualized in multiple forms. It is seen as a facilitator of transdisciplinarity in the context of general human cognition. It bridges the physical, digital, organizational, and social elements designed to enhance human cognitive abilities and facilitate the creation and sharing of knowledge (Zhuge, 2015). A cognitive infrastructure cannot exist without the constituents of conventional computational infrastructure, e.g., distributed data centers, high-speed networks, and collaborative platforms. By definition, cognitive infrastructure refers to (i) human mental models, (ii) conceptual frameworks, (iii) knowledge-intensive tools/methods, (iv) intellectualized (intelligent) systems, (iii) systems innovation resources, and (iv) entrepreneurial organizations that enable the acquisition, processing, storage, dissemination, and communication of knowledge (including data and information) to support cognitive tasks, decision-making, problem-solving, and contextualized learning.

Transdisciplinary systems science facilitates the creation of cognitive ecosystems that are supposed to capture the dynamics and regulation of the ecology of massive data flows, artificial intelligence, connected technologies, and institutional and intellectual structures. Chester and Allenby (2023) see cognitive ecosystems as an emerging and highly complex feature of an increasingly anthropogenic planet. They display the functions associated with cognition at multiple scales, including perception, information processing, internal and external communication, conceptualization, learning, reasoning, problem-solving, and memory. Várkonyi-Kóczy et al. (2013) conceptualized cognitive infrastructure as the Intelligent Space that can (i) collect information through ambient sensors, cameras, agents, and traditional and special interfaces, (ii) process the knowledge and take actions at the local level and/or in cooperation with other units, and (iii) send messages and alarms to a higher-level surveillance system.

Cognitive infrastructure and ecosystems have both tangible and intangible elements - the former supports executing the above tasks, while the latter facilitates (or inhibits) perceiving opportunities. Human attitude to learning and changing, and visionary leadership are often referred to as elements of the intangible part. Intellectualized mechatronics systems are simultaneously objects and subjects of the cognitive infrastructure. On the one hand, they are becoming an integral part of the cognitive infrastructure and ecosystem. On the other hand, being intellectualized, they (i) are fed with initial human knowledge (e.g., training data, reasoning rules, and Internet contents), (ii) work with that knowledge (i.e., aggregate, extract, transform, integrate, store, and share codified knowledge with humans and other systems), and (iii) more often than not, produce synthetic systems knowledge (e.g., explanations, projections, assessments). According to Naser and Kodur (2018), the areas where further research is needed to overcome some of the current drawbacks in realizing cognitive infrastructure and moving towards 'green' cognitive infrastructure design are related to sensing efficiency, durability, and power consumption requirements, data mining capabilities, and standardization of cognitive structural ecosystems. To be prepared for such transformation, infrastructure managers need (i) better tools to integrate cyber-technologies, (ii) to restructure how legacy systems are implemented, behave, and are controlled, and (iii) to protect them against new types of vulnerabilities (Butko and Ivanova, 2016).

7 Reflections and Future Research Options

7.1 Reflections on the Findings

The goal of this work was to contribute to a broader rethinking of the disciplinary shifts in SPDDs. Based on a systematic analysis of seminal works published in the widespread literature, this paper contributes a structured discussion of the specific findings. The intention was to impose a structure on findings by sorting them into the themes identified by the titles of the sub-sections. The paper identified five drivers of the disciplinary shifts, such as (i) scientific convergence and divergence, (ii) technology integration and synthesis, (iii) paradigmatic nearing of systems disciplines, (iv) growing level of cognitive abilities, and (v) multi-faceted natural embedding. These have been detached for a focused discussion in the paper, but they are closely interconnected and interoperate in reality. These divers, altogether but also individually, proved useful in discussing the reasons for the observable rapid changes in the disciplinary nature of SPDDs and the foreseeable developments in the near future. While the disciplinary convergences are dominating, the more and more frequent disciplinary divergences give the floor to specialization according to the fields of application and deployment.

Based on the overview of the historical developments in SPDDs, the paper has identified four epochs of moving from (first a triplet, later on a conglomerate of) fundamental fields of science to synergistically blended disciplinary fields. Concerning mechatronics, (i) classical, (ii) advanced, and (iii) intellectualized stages of evolution have been discerned, and an (iv) intelligentization stage has been envisioned for some time in the near future. We claim that the identified (i) disciplinary conjunction, (ii) multidisciplinary progression, (iii) postdisciplinary intellectualization, and (iv) transdisciplinary intelligentization stages represent conceptual milestones of the disciplinary evolution of SPDDs. In each of them, a particular shift of the systems paradigm happens under the influence of the drivers mentioned above. However, the four epochs are difficult to demarcate sharply.

The authors argue that the stages of historical evolution are characterized not only by conceptual transitions but also by intense content enrichments. These are reflected in the offerings and the impacts of SPDDs. Consequently, they also paid attention to the change in the offerings of the evolving SPDDs in correspondence with their disciplinary content enrichments. The move from physically existing offerings to apobetic offerings is obvious based on the literature and real-life experiences. The paper argues that the vector of development points from simple system-type offerings, through product-type offerings, and service-type offerings, toward experience-type offerings. To achieve an optimal apobetic experience on the side of the user/consumers, SPDDs should offer sufficient knowledge, and systems designers must have a corresponding intention, purpose, plan, and/or manifestation in their minds.

Five fields have been identified where the implications of the disciplinary progression and the paradigmatic changes are and will be the highest. These are the fields of (i) engineering mindset (epistemology), (ii) conduct of crossdisciplinary, postdisciplinary, and transdisciplinary research programs/projects, (iii) ecosystems centered engineering innovation, (iv) postdisciplinary and extramural (autonomous and life-long) approaches to engineering educations, and (v) open and evolving cognitive infrastructure. The authors had to realize that all implications of the disciplinary shifts can hardly be considered due to the wide variety of application fields and the diverse functionalities. To resolve the tension between the current disciplinary specifications (enabling scholarly fields) of SPDDs and their knowledge spaces-oriented evolution, the authors propose a novel reasoning framework and release it for a public debate. Based on the assumption of a transdisciplinary epistemology, this framework identifies the operational knowledge spaces and their teleological relationships that characterize, among many others, mechatronics, cyber-physical systems, and artificial intelligence-based problem-solving systems.

Like the other SPDDs, after some 55 years of existence, today's mechatronics encompasses an array of disciplines in an increasingly postdisciplinary scholarly colossus with fuzzy boundaries but extremely high future potential. Consequently, the complexity of its aggregated knowledge, underpinning technological platforms, and the promotion of professional activities is rapidly growing. We believe that mechatronics should be seen as a flagship representation of the fusion and synergy of technologies, and should be regarded as a philosophy supporting new ways of thinking and innovation. Though its overlap with the paradigm of cyber-physical systems is growing, it seems to keep its disciplinary identity and characteristics. These are reasons why mechatronics was selected as a demonstrative example of the drivers, stages, offerings, and impacts of the disciplinary shifts

7.2 Future Research Options

In addition to the findings concerning the drivers, stages, offerings, and implications, the authors also observed a hidden change that has not been addressed in the literature yet. This is related to the current paradigmatic nearing of the crossdisciplinary engineered systems and raises the question of where and what evolution in this context converges. The issue is that, if the technological differences between systems are disappearing, then what will differentiate them in the future on the level of system-level paradigmatic features? We have assumed that only the purpose of production will differentiate these systems in the future, and their 'teleological' identification and differentiation will be associated with their functional dispositioning. Functional disposition is the paradigmatic feature that causes intrinsic differences between the genotypes of technologically congruent engineered systems. The word 'disposition' is used here to refer to how an engineered system is designed and implemented in a given context for a particular purpose (i.e., following the logical chain of reasoning about context → purpose → disposition → manifestation). Functional design of such technologically congruent systems will define the configurational arrangement, physical/computational operations, and structural embodiment they have. We believe this issue may deserve further investigation from the viewpoint of systems science.

Concerning other necessary and possible follow-up activities, our propositions are that (i) further explorative actions are needed concerning the forthcoming stage of disciplinary evolutions since the future started yesterday, (ii) all issues should be holistically addressed rather than in a reductionist manner, and (iii) the human mindset will need to be extended by novel discoveries to cope with the majority of the emerging challenges. As Buur and Andreasen (1989) alarmed in the context of required models of advanced mechatronics, we also call attention to the unavoidable necessity of specifying new types of models. Without any obvious priority, the themes and topics proposed for further research are as follows: (i) heterogeneous (HW+SW+CW+HW) functional structures of highly intellectualized systems, (ii) manifestations of intellectualized and intelligentized system operations, (iii) socially- and culturally-sensitive intellectualized behavior of mechatronics and other systems, (iv) human and synthetic knowledge synthesis and structuring, (v) automated software integration and adaptation, (vi) recommender human interfaces, (vii) digital twins of humans and systems, and (viii) environment-dependent simulation of intellectualized behavior and services, to mention just the most important ones. Further research is suggested to validate, consolidate, and/or refine the proposed operational spaces and relations-oriented framework and test the efficiency of its further detailed versions as a means of characterization of the various manifestations of novel intellectualized mechatronics systems and to facilitate their conceptualization.

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