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ARTICLE

Educational Program Development for Post-Disciplinary Mechatronics Considering Trends, Evolution, and a Novel Reasoning Model

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ABSTRACT

Due to the intertwining scientific, technological, engineering, economic, and social trends, we need to rethink our mental models in the field of mechatronics. The authors (i) completed a broad literature survey of state of the art in this product paradigm-driven discipline, (ii) identified the trends having the highest influence on its disciplinary formation, (iii) analyzed its evolution as a unique scholarly and professional domain, (iv) overviewed its main features and offerings, and (v) examined the manifestation of post-disciplinary mechatronics. They identified five trends heavily influencing its advancement, and demarcated classical, mechatronics, and post-disciplinary mechatronics as three stages of its evolution. The formation of post-disciplinary mechatronics has jointly been enabled by (i) the need for system-level problem-solving, (ii) the emergence of cognitive design, (iii) the proliferation of artificial intelligence technologies, and (iv) the blending of cognitive, human, social, and environmental knowledge. It makes the traditional (discipline combination) models obsolete and calls for a knowledge synthesis-oriented conceptual model. The proposed conceptual framework supports epistemological reasoning about specific knowledge domains, as well as an operational analysis of their explicit relationships in various branches of post-disciplinary mechatronics. The practical utility of the conceptual framework is demonstrated in the development of post-disciplinary educational programs for assistive homecare robotics, as a case study. The paper also

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proposes follow-up research to explore further deployment possibilities.

Keywords: Influential Trends; Disciplinary Evolution; Advanced Mechatronics; Post-Disciplinary Mechatronics; New Reasoning Model

1. Introduction

As a consequence of the intertwining scientific, technological, engineering, economic, and social trends, we need to refresh our mental models. The disciplinary reasoning models of mechatronics are no exceptions to this need for a rethink. The discipline of mechatronics should be viewed as a dynamically evolving part of engineering science, rather than a static field of knowledge. As one representative of the product paradigms-driven integrative disciplines, it is concurrently evolving from ontological, methodological, teleological, and praxiological dimensions [1]. Documented in the literature, classical mechatronics has emerged as a combination of mechanics and electronics and has grown into an interdisciplinary domain of interest. Nowadays, countless definitions of mechatronics exist as a scholarly discipline and a domain of systems engineering [2]. As a discipline, it unites the knowledge, principles, and methods of mechanics, electronics, and computing in its simplest form. As a domain of system engineering, it applies a constructive approach aiming at the synergistic integration of mechanics, electronics, control theory, and computer science to design and manufacture industrial or consumer durable products and to improve and optimize their functionality, architecture, or implementation. The whole of mechatronics has many branches that rely on different combinations of (subsets of) disciplinary knowledge and focus on the realization of various application-oriented product functionalities and values [3]. As a product development process, mechatronics design (i) anticipates user needs, (ii) imagines preferred experiences, and (iii) translates these into novel product concepts.

Our previous research disclosed that certain evolutionary epochs can be identified in the disciplinary progression of mechatronics, although with vague boundaries [4]. Other seminal studies have also concluded that mechatronics is rapidly evolving from an interdisciplinary discipline, through a multidisciplinary or cross-disciplinary field of knowing, into a post-disciplinary or transdisciplinary scientific field over the last half-century [5]. As shown in **Figure 1**, these stages of evolution have been dubbed as (i) classical mechatronics (CM), (ii) advanced mechatronics (AM), and (iii) post-disciplinary mechatronics (IM). A growing level of knowledge synthesis happens in the above stages of evolution due to the convergence of scientific disciplines. The evolution process of mechatronics seems to be continuing. A remarkable observation is that, on the one hand, the lengths of the transition periods remain the same and, on the other hand, the periods between paradigmatic shifts are shortening due to growing complexity and heterogeneity. Our study also shed light on novel disciplines (or knowledge domains) that continually emerge due to the phenomenon of scientific divergence. In the end, they lead to diversification (emergence of specific application-oriented branches) of mechatronics.

With this in mind, we have completed three-stage research in which every stage had a different objective and approach (**Figure 2**). The first stage involved an exploratory survey (critical analysis) examining trends and needs based on contemporary literature. The specific goals were to (i) identify the trends having the highest influence on the disciplinary formation of mechatronics, (ii) analyze the evolution of mechatronics as a unique scholarly and professional domain, (iii) differentiate the main features and offerings of advanced mechatronics from those of classical mechatronics, and (iv) examine the current and probable near-future state of post-disciplinary mechatronics. The major findings are presented in the next sections. This explorative part of the work was driven by five research questions: (i) What are the recorded scholarly origins and the disciplinary features of mechatronics?; (ii) What trends have the major influence the evolution of mechatronics?; (iii) What disciplinary features and signature designs characterize advanced mechatronics?; (iv) What has been achieved with regard to using various artificial intelligence (AI) tools and technologies in development processes and specific mechatronics systems?; and (v) What disciplinary features and signature designs characterize post-disciplinary mechatronics? The repositories of Web of Science, Google Scholar, and Research Gate were the sources of the analyzed seminal publications.

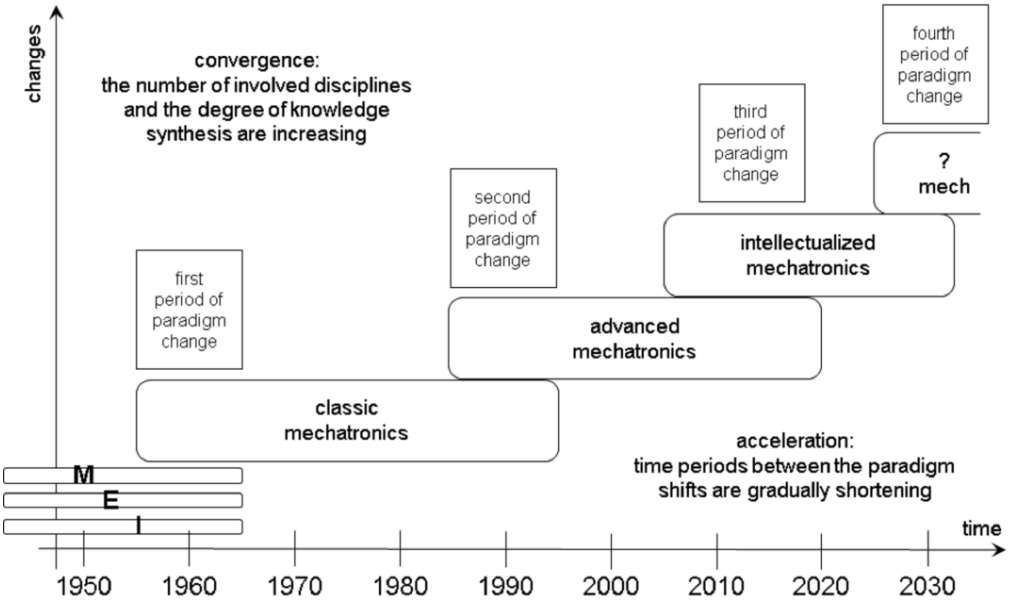


Figure 1. Disciplinary Evolution of Mechatronics.

phases and characteristics of the work	goal	approach	trigger	results	delivery
landscape of progression	overview	explorative survey	research questions	status and trends	review paper part
framework conceptualization	framing	constructive reasoning	intuitive concepts	pillars and model	position paper part
framework application	validation	demonstrative application	research hypothesis	mapping and plan	research paper part

Figure 2. CoOverview of the Phases and Characteristics of the Research Work.

The work in the second stage involved an extensive theoretical investigation of the findings related to the state-of-the-art and the five most influential trends in mechatronics as a whole. The critical trend analysis, combined with the professional ideas, knowledge and view of the authors, led to the founding principles of a novel conceptual framework for post-disciplinary mechatronics. The proposed conceptual framework covers the generic knowledge spaces and their functional relations that can be operationalized (concretized) in the various branches of post-disciplinary mechatronics. The ultimate goal of introducing the framework is to guide post-disciplinary thinking (beyond disciplinary boundaries) and transdisciplinary thinking (beyond academic boundaries) about the epistemological, methodological, and praxiological aspects of next-generation mechatronics systems. The work in the third stage concentrated on showing and validating the utility of the proposed framework. Toward this end, it has been used in a specific application context, namely, as the basis of educational program development for post-disciplinary mechatronics. The work was research hypotheses-driven (regarding the implications of the proposed novel conceptual framework, and the development and proper content of a post-disciplinary education program). This case study demonstrated not only the applicability but also the usefulness of the proposed conceptual framework in this educational context. During our study, we also aggregated insights and knowledge to underpin a reliable prognosis about the near-future manifestation of transdisciplinary mechatronics.

The three different stages of the research work are reflected in the teleological and methodological perspectives, as well as in the organization and content of this paper. The first part of the paper is like a survey paper. Its implicit message is that there are no any-to-any relations between the research questions addressed in the survey part of the work and the five current trends having the largest influence on mechatronics. The second part, focusing on constructive reasoning (framing a new model), resembles and reads like a position paper. Discussing the demonstrative application (case study), the last part of the paper reflects the general features of a research paper.

The content of this paper is structured as follows: The second section provides an overview of the currently interplaying trends, imposes a preliminary classification on them, and provides a deeper analysis of those mostly influencing the evolution of mechatronics. It provides an answer to the related research question RQ2 by identifying the five strongest and most directly influencing trends. The third section deals with the formation of advanced mechatronics as an articulated multidisciplinary discipline and interprets its disciplinary features, major manifestations, and typical offerings. It answers RQ1 and RQ3. The fourth section investigates the formation of post-disciplinary mechatronics and elaborates on its intellectualized nature, the role and effects of cognitive engineering, and artificial intelligence research and development. It answers RQ4 and RQ5 and concludes that a new way of thinking is needed to comprehend and render the fundamentals of emerging post-disciplinary mechatronics, which rapidly evolves towards a transdisciplinary epistemology and methodology. The fifth section discusses the essence of the new conceptual framework for post-disciplinary mechatronics and provides a visual model to support the reasoning about the mapping of the generic knowledge spaces and their functional relations to underpin the design of intellectualized mechatronics systems. The sixth section presents the demonstrative application example for the utilization of the conceptual framework in educational innovation in a specific branch of post-disciplinary mechatronics as well as the compiled post-disciplinary education program. We note that the terms 'post-disciplinary mechatronics' and 'intellectualized mechatronics' are regarded as synonyms and used interchangeably. The paper closes with a conclusion section, including reflections, propositions, and follow-up research recommendations.

2. Engineering in the Age of Trends

2.1. Overview of the Current Interplaying Trends

Many organizations and experts specialized in trend analysis and forecasting agree that we live in the age of trends. In fact, there are an almost uncountable number of trends that have a large influence on our current and near-future perspectives. They cause global changes and challenges, while acting in different directions, interact in complicated ways, and render an incomprehensible complexity. Below, we attempt to provide at least a non-exhaustive inventory of the trends that pose critical challenges for both academic research and artifact development.

As major scientific trends, the literature mentions (i) disciplinary convergence and divergence, (ii) contest between Mode 1 and Mode 2 science, (iii) the uncertain emergence of the possibility of Mode 3 science, (iv) superficial disciplinary integration without ontological rigor, (v) strengthening need for supradisciplinary research organization, (vi) striving for academic and non-academic alliance, (vii) overdominance of artificial intelligence, (viii) lack of science for synthetic systems knowledge, (ix) dilution of peer-review rigor and integrity, (x) rapid proliferation of low-quality research, (xi) AI-generated 'paper mill' pollution, and (xii) continuing exclusion of the South.

Hard technological trends and issues are: (i) functional complexities caused by integration of systems technologies, (ii) widely-ranging forms of the BANGM revolution, (iii) growing industrial monopolies and monoculture, (iv) privatization of GenAI, (v) cross-sectors forced AI deployment, (vi) overuse of immature large content models, (vii) shift of frontier research to proprietary platforms, (viii) sophistication of human neural augmentation, (ix) practical manifestation of quantum computing, (x) proliferation of energy-demanding forms of computation, (xi) stagnation of bio-digital interfaces, (xii) lack of epistemic watermarking of knowledge, (xiii) lack of semantic digital twins, (xiv) growing role of syndetic biology, and (xiv) danger of weaponized misinformation.

Examples of characteristic social trends are (i) global economic instability, (ii) growing digital divide and inequal-

ity, (iii) intense workforce transformation, (iv) imbalanced AI R&D concentration, (v) delayed ethical regulations for AI, (vi) exaggerated penetration of mobile systems into daily human activities, (vii) growing social embedment of socialized engineered systems, (viii) striving for new models of (engineering) education, and (ix) growing risks in social security.

Also having social flavor, overall environmental trends are (i) prevailing clean-technology deficits, (ii) need for systems modeling for societal resilience, (iii) environmental impacts of generative AI, (iv) proliferation of citizen sensing platforms, (v) appearances of unsustainable urban expansions, (vi) overreliance of renewable energy sources, (vii) unsolved prediction of natural disasters, (viii) changing political/governmental priorities, and (ix) lack of sustainability-oriented integrated systems design across sectors.

Large-scale human-related trends are (i) aging populations and declining birth rates and fertility, (ii) increased migration due to conflict, climate, or urbanization, (iii) increased demand for infrastructure, housing, and services, (iv) greater emphasis on work-life balance, mental health, and overall wellness, (v) consumer values shifting toward servicing, sustainability, and experience, (vi) parallel growth and shrink of middle-income populations, (vii) frameworks and growth of freelance economies, (viii) extreme digital dependency and networked social interaction, (ix) growing digital divide and separation, (x) greater recognition of diverse human identities, (xi) autonomous and lifelong learning are becoming the norm and the must, (xi) rise in lifestyle diseases while advances in biotechnology healthcare, and synthetic biology, (xii) unmanageably intense knowledge explosion, (xiii) spreading decline of trust in governments, media, and institutions, (xiv) frequent external and outsider view on AI, (xv) unsubstantiated striving for companion cybernetic organisms, and (xvi) irresistible academic knowledge pollution.

2.2. Trends Strongly and Directly Influencing Mechatronics

The purpose of the above overview was to clarify the complicated situation created by multiple, emerging, and overlapping trends. There are two more realities to note. First, the trends described in the previous sections differ in strength. Some are influential on their own; others have a bigger effect when combined. Second, some trends have a direct influence on mechatronics, while others have only an indirect impact. Our work focused on trends described as influential in their own right and directly observable in the evolution of mechatronics. In this section, we examine only these. Based on literature, we identified five trends with strong, direct influence on mechatronics: (i) scientific convergence and divergence, (ii) broader integration of system-oriented technologies, (iii) paradigmatic nearness of engineered systems, (iv) widely spread and trusted use of artificial intelligence, and (v) naturalization of systems for seamless environmental embedding. It is important to note that these were selected based on qualitative reasoning and reported evidence, rather than by a detailed quantitative comparison.

The convergence and divergence of sciences is a historical phenomenon. Convergence began in classical antiquity and lasted through medieval times. Divergence became dominant in the scientific revolution of the 16th–18th centuries. In the past, convergence processes were slower than nowadays. Today, it happens both over time (longitudinally) and across disciplines (transversally). Longitudinal convergence blends different scientific approaches over time. For example, empirical science gained rational approaches (for modeling) and computational methods (for simulations). Currently, theoretical and empirical methods are being extended by generative artificial intelligence, which searches and reasons over knowledge stored in clouds or edge repositories. Transversal convergence means the integration of philosophies, knowledge, methods, and values across disciplines. Divergence also occurs alongside convergence. It leads to new fields like service science, cognitive engineering, team science, biological robotics, and prompt engineering, which play a key role in many post-disciplinary mechatronics systems. The unity of convergence and divergence brings new opportunities and challenges, and will continue to affect knowledge domains. Both forms of convergence foster cross-disciplinary, post-disciplinary, and transdisciplinary science (see **Figure 3**).

The trend of integration of system-oriented technologies has also accelerated at the end of the last century. It deserves attention because of its very broad spectrum and disruptive innovation potential[6]. Concerning mechatronics, system-internal and system-external integration of technologies can be differentiated. System-internal technology integration is about the so-called HSCB (hardware, software,

cyberware, and brainware) technologies. It may actually happen in the form of (i) combination, (ii) integration, and (iii) synthesis of particular systems technologies. An example of a combination is the redundant use of dissimilar technologies to increase reliability in the context of hardware system components[7]. Integration means interlinking interoperable hardware and software technologies (e.g., arrangement of different physical sensors in a network or connecting software components from various developers directly or through control/data interfaces[8]. Synthesis means blending multiple knowledge processing mechanisms through cyberware (e.g., data streams or knowledge repositories)[9].

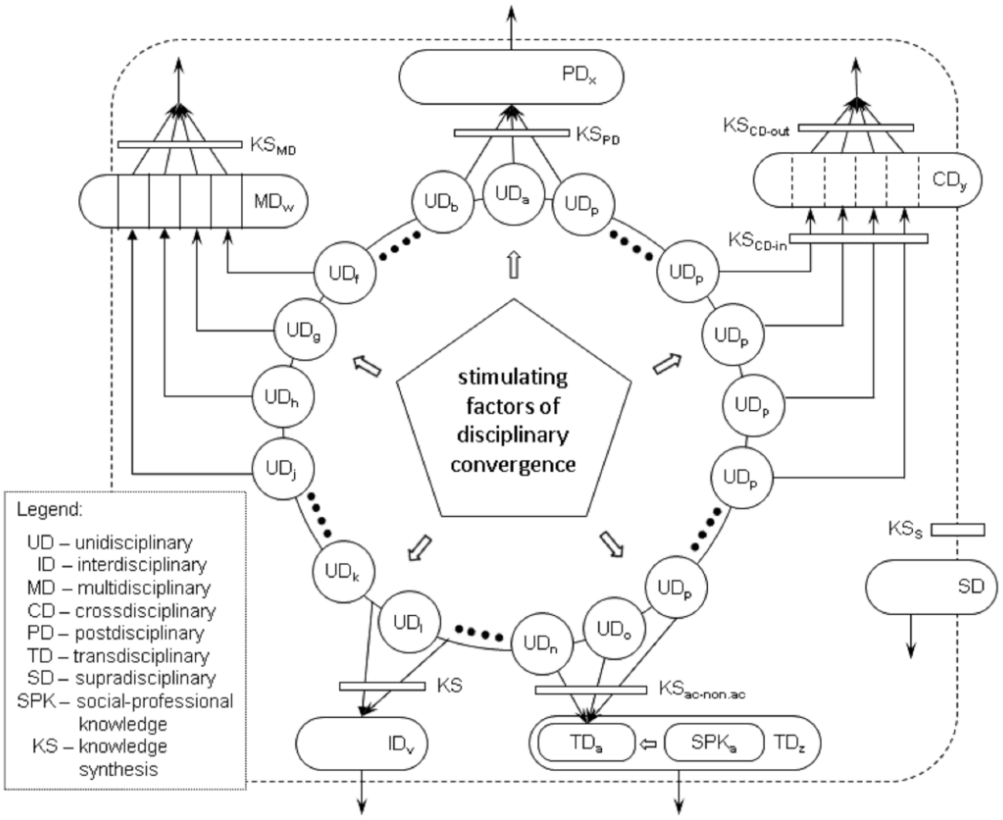


Figure 3. Interpretation of the Varieties of Disciplinary Convergences.

The third trend, the paradigmatic nearing of engineered systems, is an engineering phenomenon that is directly observable in daily practice[10]. It is about the increasing similarity and technological overlap of the manifestations of systems. This applies to systems such as socio-technical systems, mechatronics systems, cyber-physical systems, multi-agent-based actor systems, and so forth. In practice, the overlap and resemblance appear due to (i) the congruent views and expectations about the manifestations of the above-mentioned engineered systems, (ii) the congregation and extensive use of transdisciplinary knowledge, and (iii) the widespread deployment of similar (or the same) hardware, software, and cyberware technologies. For this reason, already in the near future, it will not be trivial to find (discriminative) differences among next-generation engineered systems. In simple words, this ontological trend means that the technological and engineering differences among such systems will eventually disappear, and the recognizable differences will be only in their teleology (i.e., for what objective they have been constructed and what core- and para-functions they implement). It means that just the intended/implemented functionality, together with the application environment, will remain as discriminators.

The fourth trend—perhaps the most comprehensive and abrupt one—is the ubiquitous and trusting application of artificial intelligence[11]. In the age where artificial intelligence research and development is becoming the strongest driver of economic growth, the primary target of large-scale invest-

ments, and the motivator of the boldest promises, the penetration of AI into mechatronics is obvious. The latter happens through the involvement of AI-powered development tools in engineering processes and in the form of AI reasoning and learning mechanisms used in intellectualized mechatronics systems. Approximately three decades ago, a range of expert systems was introduced to facilitate catalogue-based systematic design and configuration of production mechatronic systems. Two decades ago, rule-based reasoning and fuzzy logic approaches were subsequently employed to advance the intelligent capabilities of control mechanisms. More recently, within the past decade, methodologies such as machine learning, neural networks, and deep learning have been investigated to enable adaptive control informed by large-scale, continuous data streams. Several scholars contend that these technological enablers are fundamentally transforming the problem-solving repertoire of mechatronics and underscore the necessity of articulating appropriate future research trajectories for a post-disciplinary evolution of the field[12]. Conversely, other experts have expressed concerns regarding the potential implications of emerging cognitive technologies and integrative systems paradigms for the future of mechatronics[13].

The fifth influential trend is the naturalization of mechatronics systems towards seamless embedding in the environment[14]. Concurrently involving intellectualization, socialization, and personalization, naturalization is the basic principle emerging to drive the design and use of mechatronic systems, aligning with natural human expectations and the environmental contexts. Accordingly, physical, cognitive, social, ecological, cybernetic, computational, and contextual components of naturalness have been identified. Some experts see the goal as removing the sense of artificiality in how they appear, behave, and interact, while others claim that, depending on their kinds, new principles must be developed for the naturalization of post-disciplinary mechatronic systems. While scholarship in this area remains in a nascent and exploratory phase, the principle of naturalization is increasingly recognized as pivotal within the domain of cybernetic organisms (cyborgs)[15]. Through the integration of implants, the brain, sensory apparatus, and limbs have been functionally augmented, thereby enabling a wide array of enhanced capacities. Such advancements have culminated in the emergence of cyborg enhancement technologies whose scope necessitates unprecedented anticipatory regulation and rigorously responsible innovation[16]. The imperative to advance in this direction is underscored by the fact that millions of individuals require biological assistance or prosthetic extensions for survival or improved functionality[17]. Consequently, enhancement technologies have gradually achieved legitimacy and societal acceptance. Parallel to these developments, however, are contemporary efforts aimed at the creation of authentic human replicas - including companion entities - that replicate human morphology, behavior, and cognition with striking precision. These endeavors, while technologically impressive, engender profound cognitive, social, personal, and ethical dilemmas. As a result, the structuring of norms and frameworks governing social coexistence and interaction has emerged as a critical focal point of current research.

3. Disciplinary Features and Offerings of Advanced Mechatronics

3.1. Epistemological, Methodological, and Praxiological Augmentation of Classical Mechatronics

AM has emerged through epistemological, methodological, and praxiological enhancements of CM. The epistemological expansion has been driven by the incorporation of diverse traditional disciplines into CM's core body of knowledge. To capture these disciplines, their interactions, and the broadened scope of AM, several graphical models have been developed. These models differ in how they depict the relationships among disciplines compared to the classical representations of mechatronics. Whereas CM defines its knowledge and operational domain as the interdisciplinary overlap of the contributing foundational fields, AM approaches the source disciplines as a multidisciplinary integrator. It interprets its domain as a specialization-oriented composition of selected fragments from various disciplinary areas, which mutually enhance one another. **Figure 4** illustrates an example of such a multidisciplinary model, created by the Mechatronics Sub-Committee of the Hungarian Academy of Sciences.

Methodological augmentation concerns the involvement of offerings-oriented procedural scenarios, and the diversification of methods used in the various lifecycle stages

of AM products[18]. Key aspects of the methodological enhancement (augmentation) include: (i) integrating insights from prior research, (ii) promoting holistic systems thinking in conjunction with design thinking, (iii) employing computer-based simulation and optimization, (iv) drawing on decision theory and complexity theory, (v) incorporating principles of economics and sustainability, (vi) pursuing automation wherever possible, and (vii) leveraging artificial intelligence methods. An overview of the design models most frequently used in the development of mechatronic products was provided by Buur and Andreasen[19]. They proposed a 'model morphology' (and modeling characteristics as a convenient system for categorizing and as a means to invent properties of yet not-existent but necessary models.

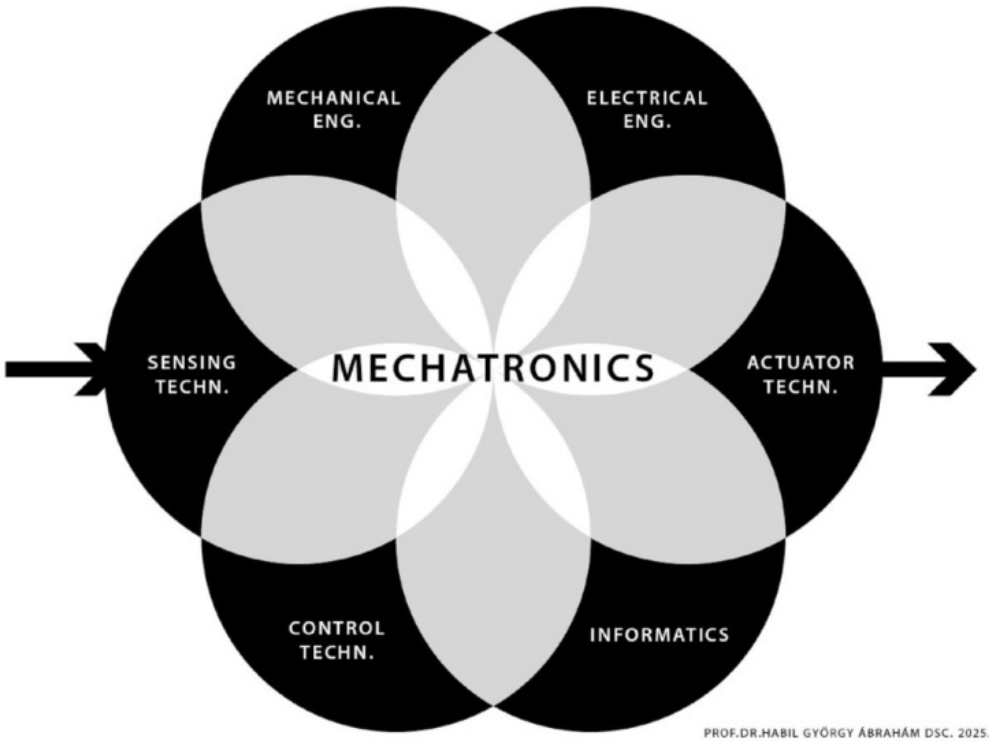


Figure 4. Disciplinary Domains of Advanced Mechatronics.

The formation of AM brought about new teleological and methodological questions for research. It needs to pay attention to issues associated with novel materialization technologies, innovation of processes and offerings, and economic, usability, interaction, and recyclability demands. The use of artificial intelligence technologies in the development process of intellectualized mechatronics systems and the deployment of AI enablers in the operation of such systems proved to be a new Janus-faced challenge, but it also poses praxiological research questions. Praxiology assumes and is based on the idea that humans naturally engage in purposeful actions, distinguishing them from reflexive or accidental behaviors. The concept of praxiological augmentation arises from examining deliberate, goal-oriented human activities. It is connected both to the evolution of AM systems and to the ways people interact with these systems in practice. Enhancing classical mechatronics through a praxiological lens involves: (i) fostering a cooperative work culture instead of isolated "throw-it-over-the-wall" practices, (ii) consistently applying leading development methodologies, (iii) utilizing advanced computer-aided tools to maximize efficiency, (iv) adhering to quality assurance standards, and (v) upholding ethical and responsible conduct[20].

3.2. Formation of an Articulated Multi-Disciplinary Field of Interest

The multidisciplinary development of mechatronics involved the blending of several academic disciplines and professional specializations into an interlinked set of knowl-

edge domains. Besides, it also necessitated the development of constructive knowledge-sharing approaches. The major progression of AM is rooted in computerization, digitalization, datafication, and informatization of the system development processes and the target offerings. It is explained by Bradley and Hehenberger that "there has been a shift in emphasis within mechatronics systems from hardware to firmware and software[21], 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".

Tomizuka, M. 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"[22]. As stated above, moving towards multidisciplinarity has influenced the practice from both an epistemological perspective and a methodological (computational) perspective[23]. This had a direct impact on the development of advanced control system solutions[24]. At the same time, it supported the integration of AM systems into Industry 4.0 for smart manufacturing[25].

A distinctive aspect of the multidisciplinary development of mechatronics is its increasing disciplinary diversity. Since the turn of the millennium, numerous new subfields within AM have emerged. These encompass specialized areas such as nano-chemistry, molecular engineering, machine vision, optical engineering, humanoid robotics, medical imaging, energy harvesting, and sound engineering, among others. They serve to complement the established, broader branches of AM engineering[26–29], with non-conventional and/or highly-specialized application-oriented ones. Some representatives of these specific branches are such as opto-mechatronics[30], hydro-mechatronics[31], micro-mechatronics[32], space mechatronics[33], nano-mechatronics[34], thermonuclear mechatronics[35], organic mechatronics[36], spectacle mechatronics[37], cyber-mechatronics[38], gadget mechatronics[39], and soft mechatronics (without striving for completeness)[40]. The diversification process goes on as new bodies of knowledge (such as cognitive, social, cultural, etc.) are included in the development processes and offerings[41]. One example is the still rapidly proliferating branch of bio-mechatronics. Its purpose is to integrate sophisticated electromechanical parts with human beings in a truly synergistic manner, well beyond what is achieved by removable gadgets such as an exoskeleton[42].

3.3. Manifestations of Advanced Mechatronics and Engineering of Mechatronics Systems

Two phenomena accompany the formation of AM engineering: (i) the application field-oriented specialization of the multidisciplinary knowledge and methods, and (ii) the diversification of the functional, architectural, and behavioral features of the developed systems[43]. It has been observed that, at the beginning of this century, the overall methodology of AM was yet strongly based on mechanically dominated products, whereas (i) significant enlargement of the involved disciplines took place, (ii) a high-level heterogeneity was developing, and (iii) an increase in the complexities of the offerings was observable. Typically, model-based systems engineering methods have been applied to develop a working system model of AM[44]. In general, the design methodology used in the development of mechatronic products was based on the principles specified in the VDI Guideline 2206. The popular V-model was applied at the macro level of elaboration, and the general problem-solving cycle of systems engineering was used at the micro level. However, the V-model has limitations in capturing the specificities of creating sophisticated mechatronic systems[45].

Advanced mechatronics brought several methodological innovations[46]. First of all, it created a digital productivity loop for virtual engineering, which, after the inception of new mechatronics offerings, supported their computer-aided virtual conceptualization, morphological and physical modeling, operation simulation, prototyping and testing, high-fidelity rendering, and preparation for manufacturing and assembly[47]. Eventually, AM has combined the mental, virtual, and physical realms of mechatronics engineering[48]. Virtual prototyping has become a standard methodology, and it has been used in all constructive stages of the development of AM offerings[49]. Virtual reality and virtual prototyping have been combined to support multidisciplinary communication among engineers representing different domains.

The above efforts have been complemented by partial mock-up making and complete functional prototyping and

time-compressing technologies (e.g., additive manufacturing, layered dispositioning, and 3D printing). In the realm of systems technologies, the advent of pervasive technologies has created fresh opportunities [50]. After the millennium, mechatronics has been expected to develop environmentally friendly solutions. This revolves around the concepts of integrated modeling of the developed systems and their narrower and broader embedding environment, and the combined application of comprehensive lifecycle assessment and environmental impact analysis as part of environmental stewardship [51].

3.4. Typical Offerings of Advanced Mechatronics Engineering

Expanding upon the previously delineated categories of electronic components, the functional techno-epistemological constituents underpinning AM systems can be identified and characterized as follows: (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) thyristor-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 [52].

Compared to the range of classical mechatronics, advanced mechatronics exhibits a far greater degree of diversification. Whereas classical mechatronics primarily involved mechanically structured machines and devices, advanced mechatronics encompasses highly sophisticated controlled systems, equipment, machines, appliances, devices, kits, and utilities. This diversification becomes even more pronounced at levels below the primary archetypes. For example, the humanoid robot "genotype," modeled on the human body to interact with human-oriented tools and environments, can be subdivided into four distinct phenotypes: (i) androids, designed to behave like humans; (ii) geminoids, capable of changing facial expressions by moving their shoulders, head, eyes, and mouth; (iii) cyborgs, which replicate human shape, morphology, motions, actions, behaviors, and communication; and (iv) animatronics, which visually reproduce human abilities in 2D or 3D virtual manikins. Each phenotype may have many different prototypes (instances) in countless forms and applications.

Advanced mechatronics engineering realizes novel types of systems which are typically sorted into the following classes: (i) data-driven systems, (ii) smart support systems, (iii) socialized systems, (iv) personalized systems, and (v) multi-feature systems [53]. Data-driven systems are equipped with continuously monitoring physical and software sensors, implement quasi-real-time data acquisition and processing, and adjust the operation of the hardware and software components accordingly through the control system. Smart agent-based systems utilize computational reasoning to perform tasks and improve their capabilities, adaptability, and autonomy within a given context. Socially aware mechatronic systems, like cobots, are engineered to engage collaboratively and sensitively with humans, other machines, or their surrounding environment.

Multi-feature systems encompass diverse configurations of the operational characteristics described above and can exhibit significantly varied forms. Personalized mechatronic systems, exemplified by humanoid robots, integrate hardware and software that are specifically designed and tailored to an individual's morphology, appearance, and behavioral patterns. The three aforementioned categories illustrate a progression from advanced mechatronic systems toward post-disciplinary mechatronics paradigms. Increasing attention is being devoted to the notion of a system of mechatronic systems, conceptualized as an integrated network of multiple interacting subsystems capable of executing complex, decomposable tasks, such as coordinated drone fleets. Research in this domain has addressed numerous engineering challenges, including control, communication, interaction, and temporal coordination.

4. Formation of Post-Disciplinary Intellectualized Mechatronics

4.1. Continuing Epistemological and Methodological Convergence of Disciplines

A significant achievement of the epoch of advanced mechatronics is that it has created mental and formal models

in which a large number of disciplines appear in supplementing relationships. On the other hand, these schemes carry certain levels of indeterminism and accidentalness because of their generality. They identify entire disciplines, rather than their knowledge domains relevant to advanced mechatronics as a whole, or a particular disciplinary branch of it. In other words, the known schemes have been constructed to capture the disciplinary amalgamation. A remarkable potential of advanced mechatronics is that the augmenting disciplines lend themselves to the emergence of new post-disciplinary branches and novel interest domains.

The third important feature of AM is that it allows the involvement of new knowledge, reasoning, and learning technologies. Using these, it can produce autonomous systems with sophisticated problem-solving abilities, adaptive control mechanisms, context-sensitive operation, and human-sensitive interaction. A fourth result is that AM has recognized that many socially-based problems cannot be addressed based on the knowledge of purely technology-oriented disciplines. In designing next-generation mechatronics systems for dealing with problems, cognitive, social, human, and sustainability-related knowledge domains should be considered with equal weight. Eventually, this fosters the move toward cross-disciplinary, post-disciplinary, and transdisciplinary (C-P-T) system engineering, knowledge integration, and product development approaches.

4.2. Formation of Post-disciplinary Mechatronics

The formation of the science of post-disciplinary mechatronics is a phenomenon observed in the last twenty years. Often positioned between smart mechatronic systems and intelligent mechatronics systems, post-disciplinary mechatronics systems (IMSs) are mainly characterized by the abilities of autonomous problem-solving and explorative self-evolution. Problem-solving intellect is architecturally and functionally integrated. Explorative self-evolution refers to system-level changes without a predefined target or expectation of a specific outcome. Eventually, the IMSs become participant in their development process, not merely in their operation and output. These abilities are the result of using a wide range of hardware and software sensors and sensor networks, and dynamically selectable and/or adjustable actuators and end effectors. Having these, IMSs are capable of operating in changing environments, with dynamic objectives, and uncertain circumstances.

The mentioned abilities are the results of sophisticated cognitive engineering and extensive use of artificial intelligence technologies. Typical such technologies are rule-based reasoning, fuzzy logic, machine learning, neural networks, or cooperating agents. IMSs can learn from experience with problem-solving in alternative contexts and improve their overall performance over time. Their autonomy means that they are capable of making decisions independently (without human intervention) based on the knowledge they have acquired partly as initial human input (e.g., training) and partly by inferring (e.g., self-learning). The latter type of knowledge is often referred to as synthetic systems knowledge. In practice, post-disciplinary mechatronics is developing under the pull of new ideas of commercializable systems as well as under the push of cognitive technologies. On the other hand, the current development of IMSs faces the generalization versus specialization trade-offs. Furthermore, IMSs also lend themselves to the verification paradox, meaning that the assessment of their correctness cannot happen before deployment, like in the case of classical mechatronics systems, because they learn and adapt post-deployment.

An important functionality of IMSs is integrated signal, data, information, and knowledge processing, which involves digital computation in the cyber domain and semantic reasoning in the intellect domain with strict timing constraints. They gradually move from causal control to intentionality-driven behavior. Based on these, (quasi-) real-time and distributed (collaborative) decision-making is pursued. In the dynamic adjustment of system behavior and internal states, real-time control strategies and data exchange play an important role. The IMSs feature both advanced human-system and system-system interfaces. Representing the next evolutionary stage, the IMSs should be designed to ensure safety-critical performance, detect, predict, and recover from system failures, and optimize resource and energy usage. The typical model-based design is complemented by run-time model development, which assumes the availability of some sort of parent model (meta-model) and contextual models of the application environment. Digital twin technology is often used for predictive analytics, performance prognostics, and system health management. Semantic inference, emotional reasoning, and abstractions-based general-

ization are still rather open issues, as is the bridging between high-level deliberative and probabilistic reasoning and low-level structured and deterministic controls. Safety envelopes around learned intellect, runtime assurance frameworks, and formal abstraction imposed on learning behaviors are studied as means of runtime proofing.

4.3. Current Features and Offerings of Post-Disciplinary Mechatronics

Two interrelated yet mutually integrable strategies for advancing the intellectualization of mechatronic systems can be distinguished: (i) the development of capabilities for autonomous problem-solving, and (ii) the facilitation of mechanisms enabling evolutionary self-management. Despite progress in these areas, numerous unresolved challenges persist. In particular, the computational realization of system cognizance—that is, the instantiation of awareness and understanding—remains a complex and intractable problem. Though it is getting widely accepted, including AI technologies in mechatronic systems does not necessarily make them intelligent. The science of post-disciplinary mechatronics recognizes the long road that leads to intelligent systems whose behavior is a high-fidelity replica of human individual, group, and collective intelligence. In the awareness of this, proposals have been made to differentiate three unique systems intelligence, namely (i) reactive intelligence (that assumes fast and robust inference and control loops), (ii) deliberative intelligence (potential of goal formation, reasoning, and planning), and (iii) interactive intelligence (social negotiation, multi-agent cooperation, and collective adaptation).

The offering of post-disciplinary mechatronics can be classified into four groups: (i) intellectualized highly adaptive systems, (ii) intellectualized autonomous products, (iii) research and development platforms, and (iv) smartificated services. Many offerings are essentially post-disciplinary versions of the offerings of advanced mechatronics. The artefactual manifestations include (i) industrial production equipment, (ii) household consumer durables, (iii) autonomous mobility vehicles, (iv) advanced robotic systems, (v) complex farming equipment, (vi) medical handling facilities, (vii) homecare service equipment, and (viii) environmental systems. A complete overview of the specific manifestations is difficult since they are largely different in the various branches of mechatronics.

5. New Conceptual Framework for Post-disciplinary Mechatronics

5.1. Recognized Limitations and the Need for a New Conceptual Framework

The ontological models of classical and advanced mechatronics focus on the disciplines deemed pertinent to particular application domains. Consequently, numerous conceptual and representational models have been proposed within the framework of AM. Their variety grows as new branches of advanced and post-disciplinary mechatronics emerge. To avoid this situation, it seems to be a more appropriate and robust approach to consider the overall (generic) knowledge spaces of post-disciplinary mechatronics and the interrelations of the operational spaces that are necessary for the realization of the (probable) functionality of next-generation mechatronics systems. Eventually, this implies a top-down reasoning that has triggered the inception of a novel conceptual framework deserving further investigation.

The newly proposed reasoning model enables a nuanced understanding of the components of C-P-T science within post-disciplinary mechatronics, as well as the systematic mapping of knowledge onto particular applications. It was emphasized that the conceptual framework should remain non-deterministic, given that the specific content of the knowledge domains and their degree of transdisciplinarity are contingent upon contextual factors such as: (i) the evolutionary stage of transdisciplinary mechatronics, (ii) the nature of knowledge associated with the particular operation spaces, (iii) the targeted application domain of the developed system (i.e., the branch of mechatronics), and (iv) the intended functionality, interactions, and implementation of that systems.

Aligned with the proposed conceptual framework, this mode of reasoning is supported by a range of contemporary studies that (i) document recent boundary-expanding and pioneering innovations in mechatronics, (ii) identify emerging disciplinary concerns associated with technologies such as cloud computing, blockchain, problem-solving methodologies, sensor fusion, swarm robotics, and knowledge-sharing practices[54], (iii) anticipate the widespread adoption of so-called intelligent control[55], (iv) highlight the unpredictable

impact of generative AI on the knowledge-retrieval and constructive processes within post-disciplinary mechatronics [56], and (v) stress the significance of advancing socially adaptive and human-centered mechatronic systems [57].

Furthermore, it has been suggested that certain disciplinary domains may become obsolete in accordance with the evolutionary trajectory of mechatronics, while new disciplines may emerge, assuming critical roles in the engineering of mechatronic systems. Within this context, the proposed framework serves as a high-level guide for the conceptualization and design of systems, based on a context-specific specification of the intrinsic relationships among knowledge spaces. Ongoing evaluations of the framework aim to assess its effectiveness in characterizing diverse manifestations of post-disciplinary mechatronics and facilitating their systematic conceptualization.

5.2. The Essence of the New Conceptual Framework

In our view, the knowledge and operation spaces of post-disciplinary mechatronics are established by the physical, cyber, human, social, and intellectual spaces. The bodies of knowledge they deliver are considered necessary and sufficient for designing next-generation (post-disciplinary, socialized, personalized, and sustainable) mechatronics systems. **Figure 5** visualizes the above-identified spaces of post-disciplinary mechatronics. It also indicates their pair-wise generic relations that should be instantiated in designing post-disciplinary mechatronics systems. Procedurally, chunks of application-dependent knowledge are derived from these knowledge spaces during the design process to specify the manifestation and operation of specific systems. Nonetheless, this process cannot be carried out in isolation from the intended purpose, operational functionality, structural architecture, inherent characteristics, and practical applications of the mechatronic systems being designed.

According to this conceptual model, the disciplines involved in the creative process are the variables, while the knowledge and operation spaces are the constants. In other words, the consideration of the enabling disciplines and their composition depends on their relevance in a given development context. In the case of post-disciplinary and transdisciplinary knowledge generation, the traditional concept of disciplines is rendered obsolete. At the same time, the conceptualization followed by the authors is in harmony with the disciplinary support of the different branches of post-disciplinary mechatronics engineering.

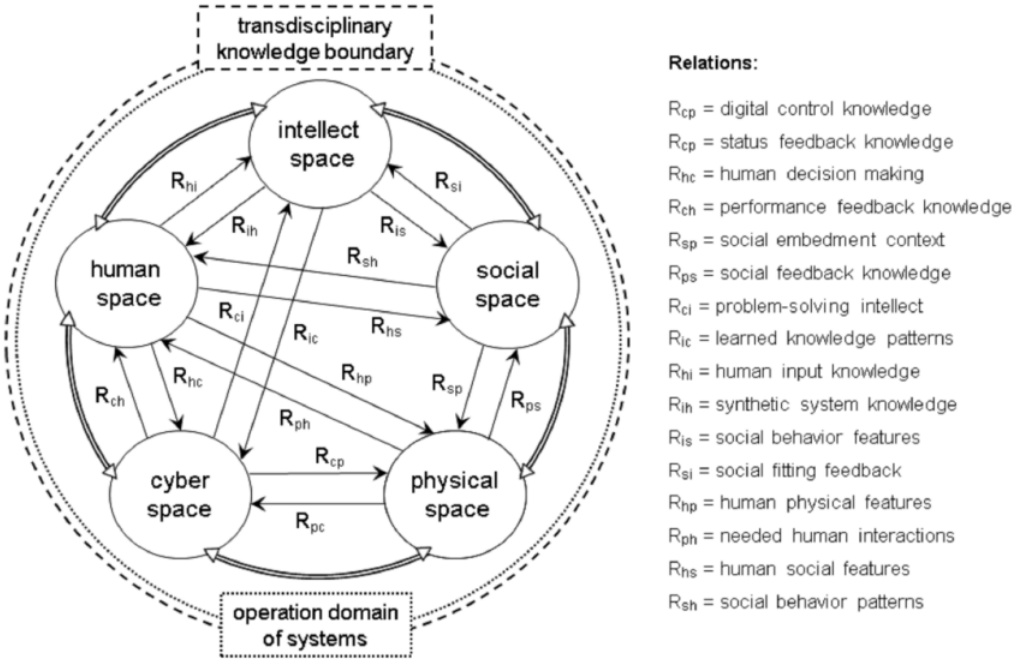


Figure 5. The Knowledge and Operational Spaces and Their Relations from a Systems Point of View.

The generic relations of the knowledge spaces vaguely indicate which concrete bodies of knowledge need to be transformed and exchanged to realize system functionalities. This concerns practically all knowledge spaces. Nonetheless, no direct correlations are posited between intellectual and physical spaces, reflecting the philosophical distinction between mind and matter. Yet, these spaces remain indirectly linked, either through the intellectual–human–cyber–physical continuum or via the intellectual–social–physical pathway. Such linkages may also be interpreted as forms of collaborative interaction between humans and systems.

As a result of the accelerating trends of convergence and divergence, the operationalization of the generic knowledge spaces may require the consideration of different scientific territories. It also applies to the existence and strengths of the abstract pair-wise relations identified over the knowledge and operation spaces in the conceptual framework. They can only vaguely hint at what knowledge needs to be taken into consideration when designing post-disciplinary mechatronics systems.

6. Utilization of the New Conceptual Framework

6.1. A Demonstrative Educational Application Example

The application example discussed in this sub-section was stimulated by the observation that present-day mechatronics education faces two major challenges. One is posed by the striving for the deinstitutionalization of learning, while the other challenge is a consequence of the intense disciplinary convergence discussed in the preceding sections from multiple contexts [58]. In **Figure 6**, these challenges are represented as two outward-pointed orthonormal direction vectors. The classical form of mechatronics education is located at its crossing. The reason is that it is characterized by interdisciplinary epistemology (course content) and a pedagogical approach relying on participatory classroom and laboratory sessions. Alongside the vectors, several epistemological and pedagogical concepts can be identified as milestones, as shown.

The overall academic objective is to develop a (i) master-level, (ii) four-semester, and (iii) post-disciplinary mechatronics education program that (iv) focuses on post-disciplinary homecare robotics, (v) deploys extramural and autonomous forms of learning, and (vi) provides balanced theoretical knowledge and practical competencies for the learners. The application example presented below is intended to demonstrate how the proposed conceptual framework can be operationalized and how it supports the development of post-disciplinary educational content and a brand-new educational program as a whole. Operationalization means using and giving a balanced comprehension to thinking in knowledge and operation spaces, and functional and operational relations. Important to note the presumption that the students are supposed to obtain the knowledge and competencies in undergraduate-level courses in: (i) mathematics and physics, (ii) mechanics and dynamics, (iii) electronics and embedded systems, (iv) systems engineering and control systems, (v) software programming and engineering, (vi) humanoid robotics and technologies, (vii) introduction to selected topic of AI, (vii) social and sustainability studies, and (viii) human cognition and behavior.

The major methodological question and challenge of program development concerns (i) the specification of the bodies of knowledge associated with post-disciplinary homecare robotics, (ii) bringing semantically different bodies of knowledge into synergy (holism), and (iii) allocation of the necessary bodies of knowledge to thematic blocks (modules) per semester. Regarded as melting pots of post-disciplinary knowledge, inquiries, and competencies, the thematic blocks are not reducible to the specific bodies of knowledge of the involved unique disciplines. There are compulsory and elective thematic blocks every semester. As a starting point for determining these, all relevant epistemological, methodological (pedagogical), and cognitive requirements should be considered. Appendix A lists the major general requirements that have been collected as relevant for the educational program.

In addition, the following technical demands and facts have been considered and met, respectively: The four-semester program should achieve a balance of (i) theoretical and practical learning, (ii) collective contact and individual autonomous study hours, and (iii) all aspects of the implementation of post-disciplinary homecare robotics. In line with the European Credit Transfer and Accumulation System (ECTS), the students are supposed to earn 30 ETCS in every semester. Considering 16-week-long semesters, 5 workdays

a week, and about 9 hours working per day, the total number of study hours is supposed to be ~ 720 hours. This means the students should work 720/30 = 24 hours for one credit, including lectures, practicums, assignments, self-studies, and other study-related activities. The total number of hours allocated to the theoretical part is 360 hours. One hundred ninety-two hours are considered for the interactive lectures, and 168 hours are allocated to online and/or offline self-study. The total number of hours allocated to the practicum part is 360 hours, from which 240 hours are for teamwork, 112 hours for self-interest-driven activities, and 8 hours for examination per semester.

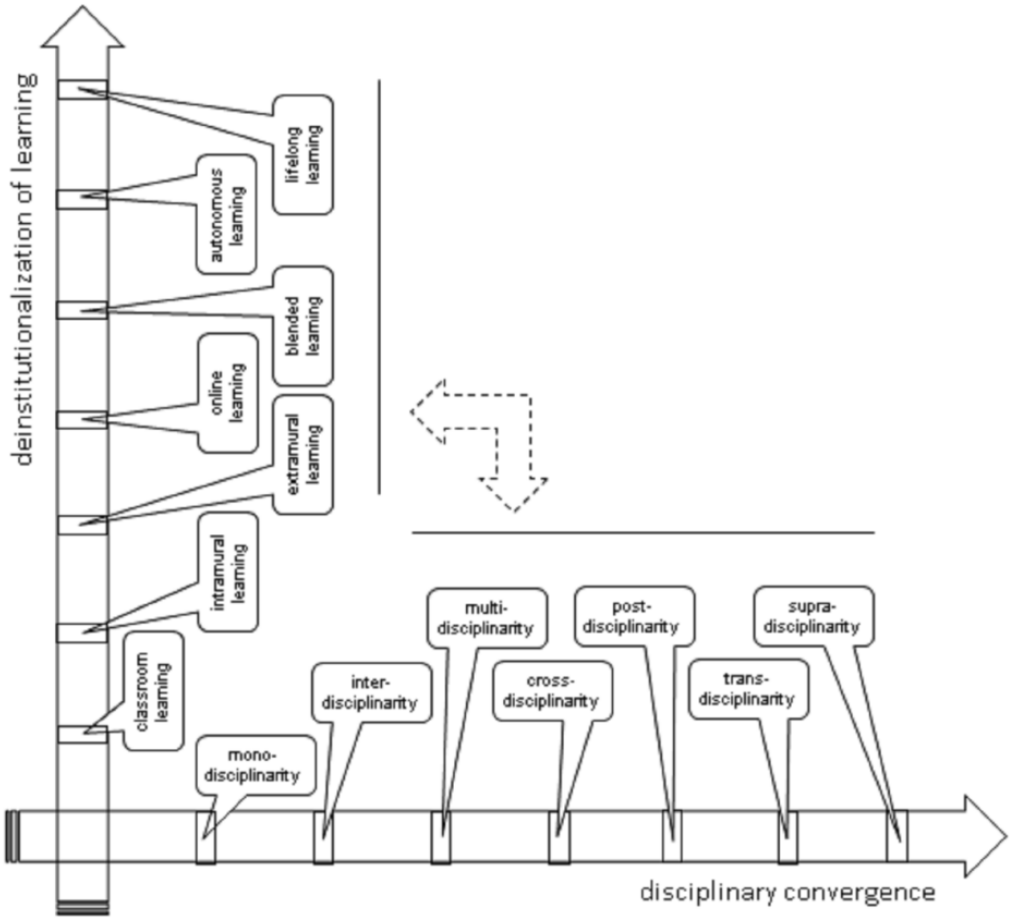


Figure 6. Two Foundational Challenges Mechatronics Engineering Education is Facing.

6.2. Operationalization of the Principles Implied by the Novel Reasoning Framework

In the post-disciplinary homecare robotics branch (specialization) of mechatronics, post-disciplinarity assumes thinking simultaneously in all knowledge and operation spaces (KOSs) as a reflective practice. The major steps of the process are shown in **Figure 7**. The abstract KOSs should be converted into program-specific, concrete, and semantically connected bodies of knowledge. The main theme of the program and requirements together determine what contents the KOSs should be instantiated with. In the post-disciplinary homecare robotics program, the preferred specific bodies of knowledge can be seen in **Table 1**. They have been defined partly by considering the requirements and partly by target-oriented reasoning. It must be noted that there is no relation between the individual concepts mentioned in a particular row, whereas the columns include those concepts based on which a given disciplinary knowledge and system operation space can be operationalized semantically. The number of concepts indicated in the columns reflects the abovementioned subjective decision concerning the concepts

of fundamental significance and the need to achieve a balanced comprehension regarding the generalized knowledge spaces.

The follow-up activities concern the investigation of the functional and operational relationships (FORs) from the perspective of the domain-specific products (i.e., according to the needs of post-disciplinary homecare robotics systems as target applications). The relation articulation process involves the operationalization of functional and operational concepts associated with these systems. Taking the physical knowledge and operation space (PKOS) and the cyber knowledge and operation space (CKOS) as a first example, the latter is associated with the former through the generation and application of digital control knowledge (relation R_{cp}), while the former is associated with the latter by providing status feedback knowledge (relation R_{pc}). (For the sake of textual brevity, let us use the acronyms introduced in **Table 1** from now on to identify the concerned KOSs.) An operational relation is established between HKOS and the CKOS by human decision-making (relation R_{hc}), while the CKOS and the HKOS are interlinked by the transferred performance feedback knowledge (relation R_{ch}).

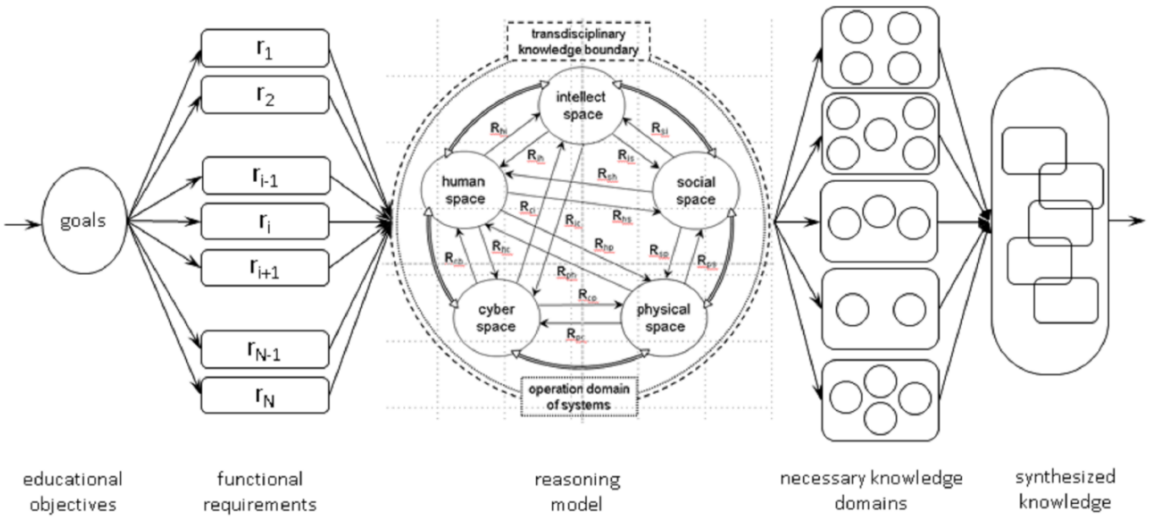


Figure 7. The Process of Thematic Synthesis of the Modules Based on the Knowledge and Operation Spaces.

Table 1. Program-Specific Bodies of Knowledge Belonging to the Various Spaces.

Physical Knowledge and Operation Space: (PKOS)	Cyber Knowledge and Operation Space: (CKOS)	Human Knowledge and Operation Space: (HCOS)	Social Knowledge and Operation Space: (SKOS)	Intellect Knowledge and Operation Space: (IKOS)
materials	signals	psychology	cultures	logic
energies	data	ergonomics	social structures	semantics
physics	information	perception	human needs	abstraction
chemistry	algorithms	cognition	modalities	mathematics
biology	software	emotion	values	modeling
mechanics	computation	intelligence	norms	learning
electronics	control	personality	aesthetics	problem solving
manufacturing	communication	behaviour	ethics	design

The SKOS and the PKOS are connected through the social embedment context of a system (relation R_{sp}), and the PKOS and the SKOS are functionally interrelated by the provisioning feedback knowledge about the actual social embedment (relation R_{ps}). The CKOS and the IKOS are functionally connected by the provisioning of problem-solving intellect (relation R_{ci}), and the relation from the IKOS towards the CKOS is about aggregating learned knowledge patterns (relation R_{ic}). The HKOS and the IKOS relationship manifests in providing human input knowledge for the operation of a post-disciplinary system (relation R_{hi}), while the essence of the generic functional relation between the IKOS

and the HKOS concerns the enrichment of human knowledge by synthetic system knowledge (relation R_{ih}).

The relatedness of the IKOS and the SKOS is exemplified by the social behavior features owned by the post-disciplinary systems (relation R_{is}), whereas a major functional relation between the SKOS and the IKOS concerns providing feedback about social fitting/matching of a system (relation R_{si}). The HKOS and the PKOS are functionally related through the set of available human physical features (relation R_{hp}), and the PKOS and the HKOS are associated through the human interactions a system needs in the physical space (relation R_{ph}). As the last relations, the HKOS is functionally connected to the PKOS through human social features (relation R_{hs}) and the PKOS and the HKOS connection is about managing social behavior patterns (relation R_{sh}).

After the instantiation of the KOSs and the specification of the FORs, the allocation of the contents to semesters and thematic blocks should be completed. **Figure 8** illustrates the results. It also shows how the KOSs and the FORs have been mapped to various theoretical and practicum blocks, which are processed either in contact or online form in the various semesters. **Table 2** provides an overview of the whole program and shows the time and credit allocation to the thematic blocks. This specialized mechatronics program is organized according to the principles of postdisciplinarity. For this reason, none of the blocks is monodisciplinary.

In addition, it can be transformed into a truly transdisciplinary program by (i) addressing complicated contextualized problems, (ii) directly engaging both academics and real-world actors in knowledge creation, and (iii) producing hybrid knowledge that transcends disciplinary and academic boundaries. It seems to be a realistic near-future objective for a post-disciplinary mechatronics program that simultaneously addresses technological, social, human, ecological, and ethical challenges. The conversion into a transdisciplinarity program presumes giving attention to aspects such as inclusiveness, contextuality, and solution orientation.

Table 2. Overview of the Thematic Blocks Per Semester.

Curriculum for the Intellectualized Homecare Robotics M.Sc. program				
	First Semester	**Second Semester**	**Third Semester**	**Fourth Semester**
Contact theoretical thematic blocks *16 x **12** = 192 hours* **(8 ECTS)**	**1TCS-A:** Scientific, technological, and societal fundamentals for intellectualized homecare robotics *16 x 4 = 64 hours* **1TCS-B:** Human perception, cognition, motor actions and emotions. *16 x 4 = 64 hours* **1TCS-C:** System sensing, reasoning, and actuation in homecare settings *16 x 4 = 64 hours*	**2TCS-A:** Functional, morphological, and environmental design of homecare robots *16 x 4 = 64 hours* **2TCS-B:** Cognitive design of intellectualized homecare robotics systems *16 x 4 = 64 hours* **2TCS-C:** Synthesis of humanoid service robots technologies and service processes *16 x 4 = 64 hours*	**3TCS-A:** Programming, control, and integration of homecare robotics systems *16 x 4 = 64 hours* **3TCS-B:** Artificial intelligence technologies in intellectualized homecare robotics *16 x 4 = 64 hours* **3TCS-C:** Postdisciplinary research in homecare robotics systems and application *16 x 4 = 64 hours*	**4TCS-A:** Innovation and entrepreneurship in homecare robotics systems *16 x 4 = 64 hours* **4TCS-B:** Sustainable circular solutions for homecare robotics systems *16 x 4 = 64 hours* **4TCS-C:** Societal, ethical, and regulatory contexts of homecare robotics systems *16 x 4 = 64 hours*
Online theoretical self-study blocks *16 x 10.5 = 168 hours* **(7 ECTS)**	**1TOS-A**: Types of current assistive robotics solutions and applications *16 x 4 = 64 hours* **1TOS-B**: Homecare problems beyond disciplines *16 x 4 = 64 hours* **1TOS-C:** Comprehension and deepening *16 x 2.5 = 40 hours*	**2TOS-A:** Robot integration in personal and public spaces *16 x 4 = 64 hours* **2TOS-B:** Postdisciplinary research in literature *16 x 4 = 64 hours* **2TOS-C**: Comprehension and deepening *16 x 2.5 = 40 hours*	**3TOS-A:** Future of intellectualized homecare robotics systems *16 x 4 = 64 hours* **3TOS-B:** Studies in selected artificial intelligence technologies *16 x 4 = 64 hours* **3TOS-C:** Comprehension and deepening *16 x 2.5 = 40 hours*	**4PCE-A** Conceptualization and approval of the postdisciplinary master's graduation project *16 x 3 = 48 hours* **(2 ECTS)**
Thematic practicum blocks *16 x 15 = 240 hours* **(10 ECTS)**	**1PCS-A:** Homecare robotics conceptualization project *16 x 12 = 192 hours* **1PCS-B:** Disciplinary research studies for intellectualized homecare robotics *16 x 3 = 48 hours*	**2PCS-A:** Homecare robotics embodiment and cognitive design project 16 x 12 = 192 hours **2PCS-B:** Postdisciplinary research studies for homecare robotics *16 x 3 = 48 hours*	**3PCS-A:** Abstract, physical, virtual, and twin prototyping and testing project *16 x 12 = 192 hours* **3PCS-B:** Industry research internship *16 x 3 = 48 hours*	**4PCE-B**: Execution and reporting of the postdisciplinary master's graduation project *336 hours* **(20 ETCS)**
Self-interest driven autonomous learning activities *112 hours* **(5 ETCS)**	**1PID-A:** Selected topics of intellectualized homecare robotics – Part 1 *16 x 6 = 96 hours* **(4 ETCS)** **1PID-B:** External professional experiences *4 x 4 = 16 hours* **(1 ETCS)**	**2PID-A:** Selected topics of intellectualized homecare robotics – Pert 2 *16 x 6 = 96 hours* **(4 ETCS)** **2PID-B:** External professional experiences *4 x 3 = 16 hours* **(1 ETCS)**	**3PID-A:** Selected topics of intellectualized homecare robotics – Part 3 *16 x 6 = 96 hours* **(4 ETCS)** **3PID-B:** External professional experiences *4 x 3 = 16 hours* **(1 ETCS)**	
Test *2x4 = 8 hours* **(0 ETCS)**	**1MTT** - Mid-term test – 1 x 4 hours **1ETT** - End term test – 1 x 4 hours	**2MTT** - Mid-term test – 1 x 4 hours **2ETT** - End term test – 1 x 4 hours	**3MTT** - Mid-term test – 1 x 4 hours **3ETT** - End term test – 1 x 4 hours	**4MTT** - Mid-term test – 1 x 4 hours **4ETT** - End term test – 1 x 4 hours
Totals	16 x 45 = 720 hours **30 ETCS**	16 x 45 = 720 hours **30 ETCS**	16 x 45 = 720 hours **30 ETCS**	16 x 45 = 720 hours **30 ETCS**

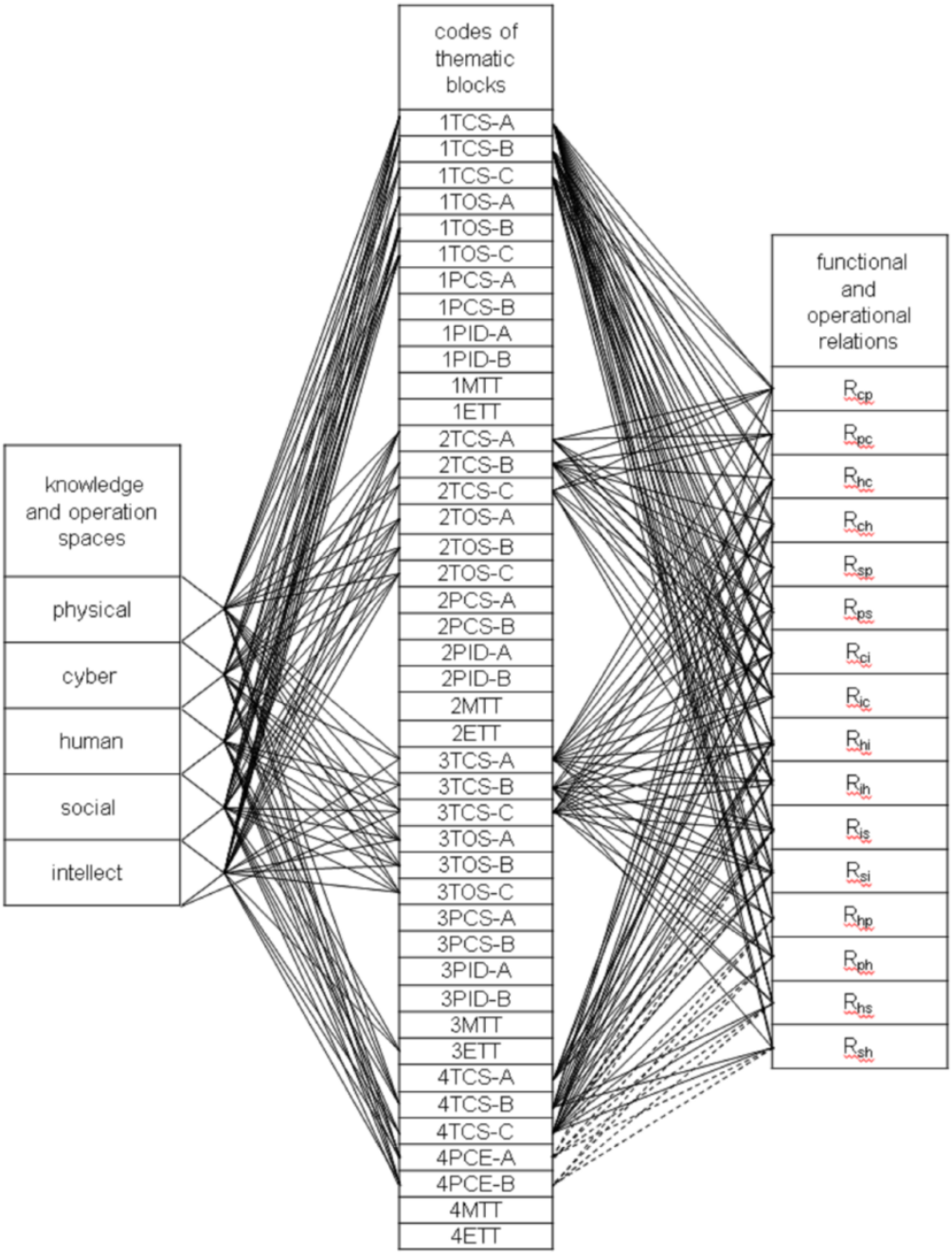


Figure 8. Mapping the Spaces and the Relations to Post-Disciplinary Courses and Practicums.

7. Conclusions

The survey part of the study provides a broad overview of the development of the discipline of mechatronics from multiple aspects and exposes important issues concerning the current state and further development opportunities. Based on seminal publications in the literature, the authors have proposed to discern (i) classical, (ii) advanced, and (iii) intellectualized epochs in the disciplinary evolution process of mechatronics [4]. In the view of the authors, these epochs are the results of the combined epistemological and technological progression of mechatronics over the decades. Though a sharp demarcation of the boundaries of the epochs is not trivial, the authors envision the manifestation of another epoch, dubbed 'intelligentized', at some time in the future. Within the identified epochs, disciplinary convergence is facilitated by various extents and objectives of computing, namely: (i) informatization, (ii) smartification,

(iii) intellectualization, and (iv) intelligentization. Also, the proliferating involvement of computing in knowledge management has facilitated the transformation of the scholarly nature of mechatronics from interdisciplinary, thorough cross-disciplinary and multidisciplinary to post-disciplinary and transdisciplinary forms. As discussed, this progression has introduced ontological, epistemological, and methodological milestones not only in the disciplinary evolution of mechatronics but also in other system-paradigm-driven disciplines. In each of them, similar paradigmatic shifts can be observed under the influence of the drivers discussed above.

The currently consolidating post-disciplinary mechatronics targets autonomous and evolving problem-solving systems for both industrial and everyday applications. A lot of knowledge is already available about such systems, but still, there are many grey or even white spots that need dedicated research. The authors warn against considering the current systems as intelligent systems. In their view, intelligent mechatronics systems should be able to present (fully-featured) human intelligent behavior.

On the other hand, there is no agreement yet on how much a complete replication of the various forms of human intelligence is needed. It is a valid question, even though various forms (textual, image, stream, verbal, etc.) of generative AI have provided a new impulse over the last two years. There is no question about the usefulness of these computational intelligence algorithms and mechanisms that extend human capabilities in the cognitive realm. Besides the associated intangibility and incommensurability, the endeavor to implement fully-featured human-like intelligence on the computational constructions of such systems is made unjustifiable by teleological reasons.

For cognitive engineering, intellectualization of mechatronics systems means both equipping them with problem-solving and knowledge, and/or with the capabilities needed to develop problem-solving potential on their own and not some form of intelligentization. In other words, the intellectualization of these systems is intended to promote autonomous real-world problem-solving, with careful consideration of prevailing economic, innovation-related, complexity, and safety factors. Intelligent mechatronic systems (IMSs) can offer significant advantages in addressing tasks that exceed the natural capabilities of humans, either in terms of feasibility or efficiency, across physical, perceptual, or cognitive domains. Nevertheless, this raises the question of whether post-disciplinary mechatronic systems might compete with next-generation cyber-physical systems due to their overlapping capabilities and reliance on comparable technological foundations.

To reconcile the tension between the current disciplinary frameworks—which underpin contemporary mechatronics—and its evolution toward interrelated, knowledge space-oriented paradigms, the authors introduce a novel reasoning framework and present it for scholarly discussion. Drawing on a post-disciplinary epistemological perspective, this framework delineates the operational knowledge spaces and their teleological interconnections, which underpin not only mechatronics but also cyber-physical systems and artificial intelligence-based problem-solving systems, among others.

The development of educational programs for post-disciplinary education in next-generation specialized mechatronics programs needs a different reasoning model than the discipline-combination models used in conventional and advanced mechatronics. The proposed new model considers the generalized knowledge spaces and their functional relations. It supports the epistemic and methodological specification of educational programs and their structuring into thematic theoretical and practicum blocks.

Regarding subsequent research and development endeavors, the authors draw the following overarching conclusions: (i) immediate and proactive measures are imperative, as the future is already unfolding; (ii) challenges should be approached in an integrative and holistic manner rather than through reductionist perspectives; and (iii) adapting to both known and emerging challenges will require a fundamentally new mindset. The authors emphasize the indispensable need to define novel transdisciplinary research paradigms [59]. They further recommend research aimed at validating, consolidating, and refining the proposed knowledge- and operations-oriented framework, which explicitly accounts for both epistemological and functional interrelations, as well as evaluating the effectiveness of its more detailed iterations in facilitating the conceptualization and characterization of the diverse emerging forms of post-disciplinary mechatronic systems.

As with everything, the presented conceptual frame-

work has limitations. Some of these can be foreseen intuitively, others can be disclosed by theoretical analysis, while yet others may be found only by empirical studies (multiple practical applications). While it is difficult to talk about empirical limitations in this state of advancement, some intuitively expectable limitations and theoretically deducible restrictions have already been identified:

- Though the conceptual framework offers a useful theoretical skeleton, it is not yet accompanied by a tested 'user guide'. Therefore, its impact may stay limited.
- It is not obvious how the application of the reasoning framework should be initiated in completely different deployments (or in a largely different branch of mechatronics engineering education). It needs not only insights, but also creativity.
- There are yet no concrete and detailed operational steps elaborated for implementation or assessment of the conceptual framework in practice. Further studies are needed to mitigate this issue.
- The graphical representation looks like a simple model. On the other hand, the detailed mapping of the generic knowledge spaces to concrete (truly post-disciplinary) bodies of knowledge needs a 'meta-knowledge' of a competent team of experts.
- The conceptual framework does not address domain-specific epistemological nuances and may not articulate (or scale) well for epistemologically highly specific and/or complicated and rapidly evolving settings. Further experimentation is necessary.
- The presented description of the conceptual framework focuses on theoretical alignment, but more empirical testing or validation with actual users or stakeholders needs to be done towards a useful application methodology.
- The conceptual framework has not been tailored and may not adapt to certain social, cultural, or institutional contexts (while the same mapping and reasoning may not apply equally well in different aspects and. environments of next-generation mechatronics).
- The reasoning framework includes neither revision nor learning mechanisms to facilitate applications. The possibility of this needs further research.
- There is a lack of context awareness, since the reasoning framework assumes that functional relations are the same across contexts, disciplines, or cultural settings.
- The conceptual framework does not address how operationalization can be distorted by bias, incomplete information, or socio-emotional factors.

In addition to the reduction or elimination of the above limitations, additional topics for further research are as follows: (i) testing the proposed conceptual framework in applications other than of educational nature, (ii) conceptualization of transdisciplinary educational programs from epistemological and methodological points of views, (iii) consideration of autonomous and lifelong learning in post- and transdisciplinary education programs, (iv) manifestation of intellectualization and smart system operation, (v) elaboration of combined (HW+SW+CW+BW) functional structures and heterogeneous behavioral models, (vi) socially-sensitive behavior of post-disciplinary mechatronics systems, (vii) synthesis and structuring of human and synthetic knowledge, (viii) automated integration and adaptation of software constituents, (ix) development of context-aware recommender human interfaces, (x) combination and simulation of digital twins of humans and systems, and (xi) environment-dependent simulation of post-disciplinary behavior and services, to mention just the most important ones. The order of listing does not reflect any obvious priority or stated order of importance.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

Below is the list of general (epistemic and pedagogical) requirements for the education program for post-disciplinary homecare robotics. The new educational program should:

a. be an internationally competitive study at the concerned highly-ranked university of technology for transnational master students
b. equip the learners with a cutting-edge theoretical foundation and a wide set of competitive practical competences (combining research and industry readiness)
c. focus on the branch of mechatronics systems, called post-disciplinary homecare robotics systems, that provide support and care for elderly with normal abilities and assumed disabilities
d. realize a strong thematic relationship between the theoretical part and the practicum part
e. address present and near-future real-world problems of post-disciplinary homecare robotics and facilitate the mastery of the subject matter by the learners
f. develop a holistic view on post-disciplinary homecare robotics from technological, design, implementation, and deployment points of view
g. break down traditional engineering silos and adopt a genuine post-disciplinary approach by integrating knowledge across relevant interest domains
h. synthesize post-disciplinary knowledge across the source disciplines and include it in (compulsory and elective) theoretical and practicum modules (thematic blocks), instead of traditional disciplinary courses
i. facilitate that the graduates of this program will not be "experts in parts" but "thinkers in wholes", and ready to lead post-disciplinary and transdisciplinary innovation projects
j. follow a pedagogical approach that is characterized by the procedural concepts of acquaintance, integration, reflection, and practice in context
k. include practicums that focuses on the integration of HSCB (computing hardware, software, cyberware, and human brainware) constituents
l. achieve a balanced comprehension of the physical, cyber, intellect, social, and human knowledge and operation spaces
m. shed light on all functional and operational relationships and dependences between the above knowledge and operation spaces from the view point of post-disciplinary homecare robotics systems
n. prepare the learners to combine physical hardware with cyber algorithms, problems solving intellect, human factors, and social contexts to achieve useful, effective, and safe homecare robot designs
o. include a cross-disciplinary capstone design project in every semester and one mandatory thesis project
p. clarify the role of cognitive design/engineering of mechatronics systems and the computational intelligence technologies in achieving post-disciplinary system operation
q. address social, human, ethical, safety, utility, and sustainability aspects of post-disciplinary homecare robotics, besides user-centered system design
r. adhere to European regulatory contexts and ISO standards
s. develop competencies in human-centric design and development of robots and their integration in homecare environments and/or biomedical applications
t. operationalize complex assessment that involves post-disciplinary content and reasoning exams, proving design competencies and designed artifacts, and openness to self-reflection and peer reviews
u. prepare for self-defined online autonomous learning and life-long learning

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