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Extended editorial:
Past, present and future of behaviourally adaptive engineered systems

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Abstract

Keywords: Engineering systems, adaptive systems, behavioural adaptation, self-adaptation, enabling resources

1. Introduction

When we input 'behavioural adaptation' as a search term in a common search engine, it will immediately be extended with supplements such as 'of animals', 'of plants', 'of humans', etc. However, we can hardly see words such as 'of systems' or 'of artefacts' or 'of products' as a supplement in the drop-down menu of this search engine. One can interpret this as a kind of indication that the research in behaviourally adaptive engineered systems has yet not received enough attention. On the other hand, searches with refined keywords bring up a huge number of publications that addressed very different aspects and issues of complex adaptive systems, self-adaptive autonomous systems, and proactive smart systems. At the dawn of the fifth industrial revolution (a disruption caused by non-natural intelligence), this latter can be explained quite easily. On the one hand, we are witnessing a transfer of behavioural adaptation principles of natural and social systems to the domain of complex engineered systems, accompanied by efforts to implement effective computational mechanisms. On the other hand, one can observe an under-developed, often confusing vocabulary of system adaptability and adaptation, which makes navigation on the sea of related concepts difficult.

Notwithstanding the growing number of publications, the very issue of system adaptation, in particular self-adaptation at runtime deserves more scientific attention. Actually, this was the reason and motivation behind proposing this special issue, which intends to provide a concise overview of the most important concepts and viewpoints and to contribute to the broad field of main stream developments. As far as this introductory article is concerned, we believed putting natural adaptation and system adaptation face to

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face would help understand the similarities and the differences. Natural behavioural adaptation has to do with the phenomenon and mechanisms of adaptation of organisms. In the literature, three types of adaptation are distinguished: (i) behavioural adaptation (that includes all responses of an organism that help its survival/reproduction), (ii) structural adaptation (that involves all stimulated changes of the features of an organism, and (iii) physiological adaptation (that enables all bodily processes that support survival of an organism). Though both structural and physical/functional adaptation play an important role in the case of engineered systems too, we will concentrate on finding answers to questions related to behavioural adaptation. Eventually, behavioural adaptation is closely associated with the mentioned two other forms of adaptation, or can even be deemed to be a consequence of them. For instance, in the natural world, migration of birds is a form of behavioural adaptation that is facilitated by their structural adaptation that makes them capable to do this. Behavioural adaptation of engineering systems shows many similarities, but also many differences …

2. Revisiting the fundamentals

It is broadly accepted in biology that adaptation is the result of evolution, which is comprehended as changes in a species over a long period of time under external influences. Evolution is established by incrementally aggregating sudden changes. The growth of structural and functional complexity during evolution has been accepted as a *de facto* law (Heylighen, F., 1996). With regards to its nature, evolution can be constructive (appearance of new features that help survive and thrive) or destructive (diminish of existing features that are not needed for survival). According to this general view, the essence of biological adaptation is the concurrent appearance of: (i) evolutionary changes in physical features, and (ii) performing routines in alternative ways. Eventually, this makes structural adaptation and behavioural adaptation inseparable. Adaptation can be instinctive or rationality driven, and may be observed in the case of individuals, groups and populations. Adapted behaviour can be learned by one individual and passed on to another one, or collectively and passing it from a generation of a population to another generation, both behaviourally and genetically. Usually, positive correlations were found between the rate of adaptation, the intelligence of behaviour, and the level of socialization. The biological adaptation, which is typical for adaptation of animals, and the rational adaptation of humans represent two largely different mechanisms. Emergence and mutation play a significant role in the former one, while self-organization appears in the latter one.

Owing to the progress of system engineering and technologies, engineered systems have become capable to realize various levels of structural and behavioural adaptation, but not exactly as natural systems do. Their self-adaptation: (i) is driven by different purposes, (ii) is based on different principles, and (iii) needs to happen in a short timeframe. Both individual system implementations and systems of systems can have the capability of functional, structural and behavioural adaptation. Structural adaptation can be morphological, topological or architectural. Adaptation happens at run-time and according to a purpose that the system is supposed to realize. It may manifest as self-tuning, self-adaptation, self-evolution, or self-reproduction.

The relationship of adaptation and evolution is different in the context of self-adaptive engineered systems from that one existing in the context of natural adaptive systems. As shown in Figure 1, the relationship is actually reverse. In our view, it is not really a dilemma whether adaptation is part of evolution or evolution is part of adaptation. They are seen as different forms of self-organization of artefactual systems. In our interpretation system adaptation is a change, which does not introduce functional or architectural novelty. System evolution is however seen as a progressive change that creates and aggregates novelties. In other words, the extent of the introduced novelty, rather than the time period needed to arrive at it is important. Both technical adaptation and evolution concern one instance of a system, rather than generations of a system. The next generation of self-adaptive engineered systems will most probably be able to behave not only as individual organisms do, but also as families, communities and organizations perform. De Wolf, T. & Holvoet, T. (2005) contrasted the phenomena of emergence and self-organisation, and elaborated on the benefits of combining them in systems.

3. Setting the stage

There is a debate in the literature on whether adaptability is the cause of complexity of systems or adaptability is a result of complexity of systems. Some contemplate all complex systems as adaptive and use the term 'complex adaptive systems' to refer to them. The most frequently differentiated categories of complex adaptive systems are natural, artificial and social systems. However, most of the observable systems overlap these categories, i.e. reflect the features of more than one category. Adaptation of systems means not only changing functionality, architecture or operation, but also providing the resources necessary for adaptation in the right form, on the right place, at the right time, and in the right way. This issue seems to be somewhat underexposed in the accessible literature and, most probably, also in current research.

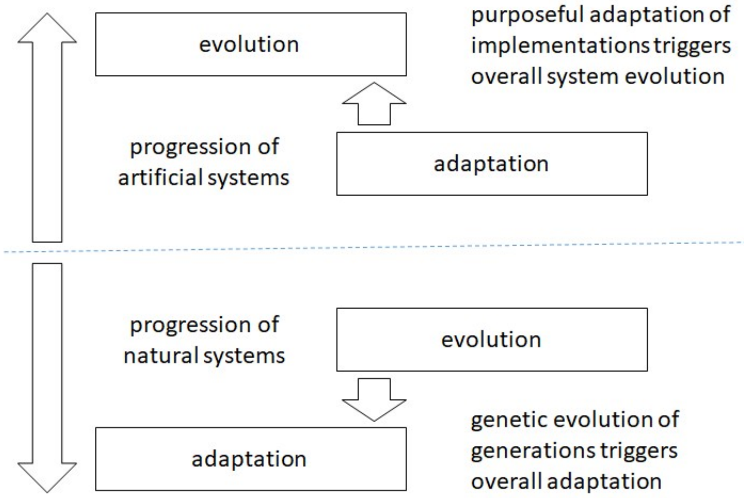

Figure 1 The mirror view on adaptation and evolution of natural systems and engineered systems

We have completed a structured literature survey with a dual goal: (i) to sketch up the current state of research and development in the field of behavioural adaptive engineered systems, and (ii) to create a reference with regards to introducing the novelties of the papers contributed to this special issue. We used the reasoning model shown in Figure 2 as a starting point for our survey. We wanted to cast light on the most important issues of the past (from the beginning until the end of 1990s), the present (from the millennium until today, and the near future (from now on) of the concerned domains of research and development. Our overall findings are shown on the right side of Figure 2. The blocks not only show the general research topics for each period, but also demonstrate how the research concerns progressed and became articulated. We used the same structuring of the research issues and arranged the findings of the survey accordingly in the sections below.

4. The past of developing behaviourally adaptive engineering systems

The phenomenon of behaviourally adaptive engineered systems was hardly studied in engineering research fifty years ago. Thus, it is practically untraceable in the then engineering literature. It was often the subject of various philosophical speculations and science fiction writings. Holland, J.H. (1962) was among those pioneers (visionary thinkers), who dealt with the issue of system adaptation. Based on the analogy of generational adaptation of biological

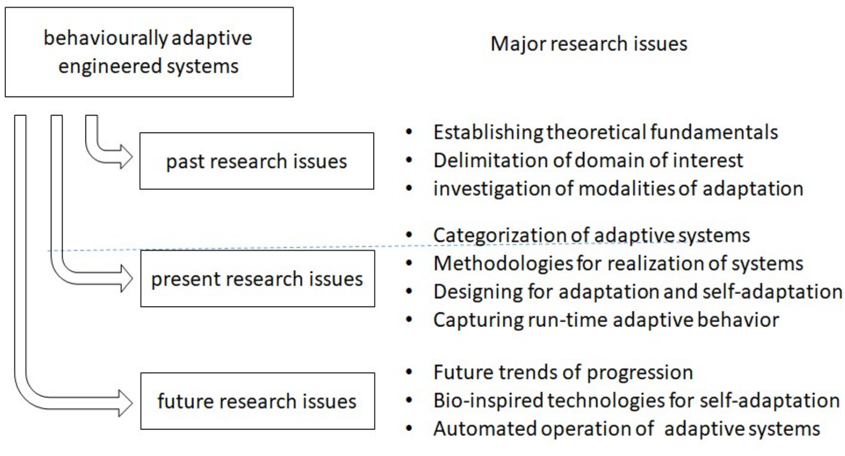

Figure 2 The reasoning model used in the survey

systems, he proposed a theory and conceptualized a framework of engineered systems with adaptation abilities. Holland, J.H., & Reitman, J.S. (1977) studied adaptive algorithms for such kind of cognitive systems. Adaptation was seen as an outcome of an intense interaction between a system in a state and its environment. Accordingly, adaptability was defined as the ability to rapidly adjust behaviour according to changes in the operational objectives and conditions, and to the dynamics of the environment. Over the years, multiple theories of adaptive systems have been worked out and extended, among others, to organizations (Dooley, K.J., 1997), supply networks (Choi, T.Y. et alias, 2001), clinical practice (Brown, C.A., 2006), public service systems (Rhodes, M.L. & MacKechnie, G., 2003), agile software development (Martín, H. et alias, 2006), disaster resilience [Coetzee, C. et alias, 2016), and educational systems [Keshavarz, N. et alias, 2010). The law of adaptation was informally stated as: Every adaptive system converges to a state in which all kind of stimulation ceases (De Lope, J. & Maravall, D., 2009).

Large gaps were observed in terms of the conceivable purposes of adaptation and the utilization of this ability. It was recognized that the variety of the systems that may adapt in one way or another was rather wide. From a practical perspective, two major forms of systems adaptation were identified, namely, (i) stakeholder completed adaptation, and (ii) system self-adaptation. The latter was regarded as a strategy of changing the architecture and/or operation of a system without human interaction. Research was gradually diversified through inquiries into functional, structural and behavioural system adaptation. The situation when the operation of a system changes without structural adaptation was understood as functional adaptation. Structural adaptation was defined as a situation when the topology (the included entities and their connectivity) of a system is changed (e.g. from a centralized structure to a distributed structure). The situation when functional adaptation and structural adaptation concurrently happen was termed as hybrid adaptation. Lastly, the situation when hybrid adaptation happens under a heavy influence of the operational environment was called behavioural adaptation. The objective of studying behavioural adaptation was to find working principles based on which systems could react to changes so that their desired behaviour can be kept within specified limits or patterns.

5. The present of developing behaviourally adaptive engineering systems

The last 20 years witnessed many theoretical refinements as well as a move towards practical realization of behaviourally adaptive engineering systems. Pike, A. et alias (2010) contributed to the theoretical understanding of system resilience, adaptation and adaptability. In the area of rational elaboration, Kurtz, C.F. and Snowden, D.J. (2003) proposed to divide systems into four groups so as (i) simple, (ii) complicated, (iii) complex, and (iv) chaotic systems, depending on the degree to which their cause-effect relationships can be predicted. Gleizes, M.-P. et alias (2007) elaborated on the essence of engineering systems, which generate emergent functionalities. It became accepted if, like living organisms, systems are to adapt to their environments, then they need to use: (i) sensory perception (detecting and anticipating changes in the environment), (ii) cognition (reasoning about perceived changes and deciding on the best action), and (iii) actuation (controlling the implementation of cognitive decisions). Systems equipped with this capability were variously called: (i) self-tuning systems, (ii) self-optimizing systems, (iii) self-resilient systems, (iv) self-healing systems, (v) self-organizing systems, (vi) self-adaptive systems, self-managing systems, (vii) self-evolving systems, or (viii) self-reproducing systems. The sequence of the names reflects an increase in the capability of concurrently implement functional, structural and behavioural changes by a system on itself.

Kephart, J.O. & Chess, D.M. (2003) distinguished four principal types of high-level system adaptation: (i) automatic self-configuration, (ii) continual self-optimization of performance and/or cost), (iii) detecting, diagnosing, and repairing problems caused by bugs/failures by self-healing, and (iv) self-protection against malicious attacks or cascading failures). The potentials of autonomous operations also grow in this order. Weyns, D. et alias (2012) concluded that there are different communities behind these notional descriptions, as well as different vocabularies. Having recognized the fact that several classification proposals exist that intend to capture either the variations in the system awareness and respond capabilities, or the level of pre-programming and run time learning, Sabatucci, L. et alias (2018) proposed a meta-model that describes the typically identified four types of self-adaptive systems. This model includes all generic elements of a smart adaptive system and embraces all the elements that implement the different types of self-adaptation.

Designing for adaptation is a modelling paradigm that defines and configures adaptation mechanisms and strategies in the systems design phase. Designing for self-adaption focuses on the opportunities and the resources of adaptation at the runtime. Cansado, A. et alias (2010) proposed a formal framework that unifies behavioural adaptation and structural reconfiguration of components and showed the advantages in the context of reconfiguration of a client/server system in which the server has been replaced. Chandra, A. et alias (2016) analysed and compared architecture frameworks currently proposed for designing self-adaptive systems, which include the observe-decide-act (ODA), the MAPE-K, the autonomic computing paradigm (ACP), the observer/controller architecture (OCA), etc., which are rooted in organic computing research and are intended for different types of distributed systems, such as swarms, systems-of-systems, crowd computing, computing entity populations, multi-agent systems, etc. Hummaida, A.R. et alias (2016) presented cloud resource management (allocation of a shared pool of configurable computing resources) as a typical example of demand-enabled system adaptation. The survey completed by Muccini, H. et alias (2016) explored that typical levels of system adaptation are the application layer and the middleware layer (rather than the communication, service or cloud layer), and that MAPE, agents, and self-organization are the dominant adaptation mechanisms. Moreno, G.A. et alias (2015) and (2016) studied the issues of using probabilistic model checking and uncertain decision making to support proactive self-adaptation, respectively. Multi-agent planning was considered by Marc, F. & Degirmenciyan-Cartault, I., (2003) as a coordination model for self-organized systems, while Miralles, J.C. et al (2009) proposed a peer-to-peer cooperation for multi-agent system adaptation.

Haghnevis, M. & Askin, R.G. (2012) presented a framework for modelling engineered complex adaptive systems. Braberman, V. et alias (2015) proposed a reference architecture for configuration and behaviour self-adaptation. These and other methodological issues have first been recognized in the field of software and embedded systems design/engineering. Notwithstanding, there has been no clear view on how self-adaptation actually contributes to tackling the challenges of engineering and managing truly complex software systems. In the last decade, many studies addressed the adaptability and self-adaptation issues of cyber-physical systems (CPSs), including advanced robotics (Horváth, I. & Gerritsen, B.H., 2012). The study of Tavčar, J. & Horváth, I. (2018) tried to explore and synthesize the principles of designing smart cyber-physical systems for run-time adaptation. The related literature claims that self-adaptive CPSs should be capable to adjust or change their structure, functionality and behaviour at run-time as a response to emerging requirements, changing objectives, environments, and contexts that may be unknown at design-time. Wolfinger, R. et alias (2008) approached the issue of runtime adaptation through product line engineering and using plug-in techniques.

Horváth, I. et alias (2017) proposed a comprehensive model of self-adaptation of advanced cyber-physical systems. This assumes that self-adaptation simultaneously progresses in the interrelated domains of architecture and operation (i.e. in the system space (SS)). Every point of SS represents a particular architectural and functional manifestation of the system, which is in an operation state (OS). A 0G-CPS is designed to be in an initial system space (ISS) in its designed operation state (DOS). A 1G-CPS can shift its DOS to an optimal operation state (OOS) inside ISS (Figure 3.a). The chosen OS can be anywhere in SS, unless unfeasible. A 2G-CPS can place its OOS outside ISS and extend its ISS, but afterwards it operates in the extended system space (ESS) (Figure 3.b). A 3G-CPS may extend its ISS to various EESs repeatedly and may dispose its OOS to any one of these dynamically (Figure 3.c). A 4G-CPS may create other disjoint ESSs to its ISS/EES) in various manners and may place its OOS to anyone of these EESs (Figure 3.d). Called reproduced system space (RSS), the disconnected EESs are associated with distributed and decentralized replicas of the ISS. Janošek, M. et alias (2013) discussed how structural and operational parameters can be instruments of regulating the behaviour of a system. He used the leverage point theory of and recognized these characteristic patterns of the system's behaviour using neural networks (Meadows, D.H., 1999). This system cognizance-based approach to adaptation required subsequent mediation of the system's behaviour through selected parameters and their action ranges based on pre-prepared expectations of what will happen if the system's behaviour exhibits a known characteristic pattern.

In the last two decades, both designing for adaptation and designing for self-adaptation have become protruding design methodological issues in application contexts. This is also influenced by the high variance of types and applications of engineered systems. Recently, system adaptation has been identified as a key technology towards automated driving (Haböck, U. et alias, 2016). In addition to traffic management, energy provisioning, and manufacturing environments, adaptive systems have been penetrating into the domain of medical systems too (Abbod, M.F. et alias, 2002). Brown, C.A. (2006) elaborated on the application of complex adaptive systems theory to clinical practice in rehabilitation. Li, C. et alias (2016) developed a smartly adapting cyber-physical system solution for monitoring and enhancing rehabilitation of stroke patients.

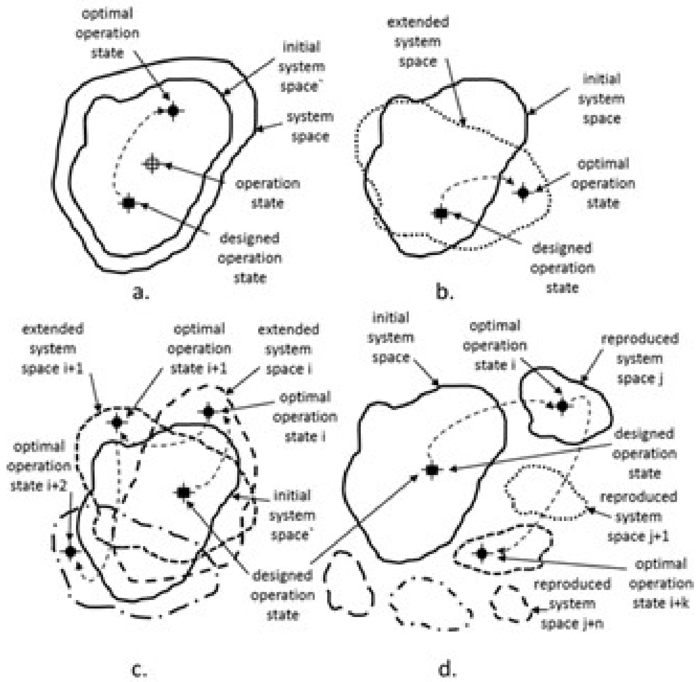

Figure 3 Model of adaptation of various cyber-physical systems

One of the challenging questions today's research is facing is how to get to and operationalize actionable insights by systems themselves. The current generation of adaptive systems are closed systems, and suffer from limitations with regards to the theoretical adaptation of functionality (modes of operation) and architecture (management of resources). As observed by Bruni, R. et alias (2015), the requirements engineering for these systems typically happens in a black-box perspective, while their modelling and programming usually happens in a white-box perspective. On the other hand, requirement engineering should be integrated with runtime behaviour (Feather, M.S. et alias (1998). Various approaches have been proposed to help self-adaptation at runtime (Filieri, A. et alias, 2016). Kramer, J., & Magee, J. analysed the architectural challenges of system self-management. Gerostathopoulos, I. et alias (2016) proposed the so-called 'invariant refinement model/method' that supports architectural self-adaptation at runtime and integrates the mechanism of predictive monitoring of operational uncertainties. Garlan, D., & Schmerl, B. (2002) and Garlan, D. et alias (2004) proposed a method for model-based and architecture-based self-adaptation, respectively. Nevertheless, designing automation for engineered complex adaptive systems in the industry remains a genuine challenge (Kaber, D.B. et alias, 2001).

6. The future of developing behaviourally adaptive engineering systems

Evidently, it is not easy to make a forecast concerning the future. Linear extrapolation from the present day research and trends may prove to be unreliable or even incorrect due to the rapid developments. Nevertheless, certain strands of research may seem to be robust and road paving. It seems that a strand of research of high potentials is using natural (e.g. biological) analogies in behavioural adaptation with respect to changes in hardware, software and cyberware constituents of systems. Negoita, M.G., & Hintea, S. (2009) investigated bio-inspired technologies for the hardware of adaptive systems. Phillips, B.J., & Blackburn, M. (2016) discussed that the physical architecture observed within the neocortex will in the near future be more frequently and sophisticatedly implemented in adaptive systems.

Not only service-oriented structural and functional adaptation, but also content and context adaptation seem to be a hot research in the near future. Khazaei, H. et alias (2018) identified the opportunity of establishing increasingly distributed and dynamic system architectures that provide unprecedented flexibility in creating and supporting applications as an advantage of adaptability, but emphasized the importance of balancing complexity and programmability. Towards that end, they proposed the idea of moving from self-adaptation to ADaptation-as-a-Service (ADaaS). Another concept is, as discussed by Geoffrois, E. (2016), to make adaptive systems capable to learn not only from their own experiences, but also from the feedback provided by the users about their outputs and performance, and from each other experiences (Jiao, W., & Sun, Y. (2016). As a general objective, Essa, A. (2016) claimed that next-generation application driven adaptive systems, such as adaptive learning systems, should have generic characteristics such as (i) cost-effective, (ii) accurate, (iii) efficient, (iv) up-scalable, (v) flexible, (vi) generalizable, and (vii) transparent are the most. The above picked out examples provide evidence that research will continue towards a deeper understanding and the development of behaviourally adaptive engineering systems.

7. The novel contribution of the included articles to research and development of behaviourally adaptive engineering systems

This special issue is based on a selection of the best papers submitted to the Twelfth International Symposium on Tools and Methods of Competitive Engineering (TMCE 2018). This event of the long-existing and influential series of TMCE Symposia was held in Las Palmas de Gran Canaria, Gran Canaria, Spain, from 7 May 2018 until 11 May 2018. This symposium was co-organized by University of Las Palmas de Gran Canaria and the Delft University of Technology. Originally 13 papers were considered, out of which seven qualified for inclusion in the special issue in the end. In one way or another, each of these seven papers contributes to the main theme of the special issue: "Towards behaviourally adaptive engineering systems". Most of them reports on enablers that support establishing self-adaptation. The selected papers have been pre-reviewed by the co-guest editors in order: (i) to attain the best possible quality, (ii) to have the highest possible relevance for the special issue, and (iii) to achieve coherence in the special issue. This latter aspect proved to be the most challenging, while the other issued were easier to manage based on the understanding and the nice cooperation of the authors. The revised manuscripts were peer reviewed by members of the review panel and the editorial board members of the journal. None of them changes the world in itself, but together they represent the needed main strands of research and useful contributions.

The paper following this editorial, entitled '*Components and Interactions: Paving the Way to Model Agent-Based Cyber-Physical Social Systems*', is a contribution to theoretical understanding and ontological clarification. The author, *Stefano Borgo*, compares two contemporarily popular paradigms, cyber-physical systems (CPS) and socio-technical systems (STS) of system science and engineering. These paradigms serve as a basis for modelling, simulation, implementation and analysis of systems with complex adaptive behaviours. The author asserts that these are complementary and able to support modelling and realization of adaptive behaviour on both component and system levels. It is an interesting observation of him that, contrary to the historical and methodological differences, current day research in CPS and in STS tends to tackle the same issues. Therefore, similar functionalities and features appear in these types of systems. The author suggest that integration of expertise is necessary in the two domains and that it can be fostered by introducing a suitable conceptual framework and a coherent characterization of agent-based adaptive systems. Eventually, the main contributions of this paper are: (i) characterization of the class of agent-based cyber-physical-social systems, and (ii) development of an ontological framework based on the traditional notions of component and interaction. The paper introduces and motivates a set of initial core distinctions, and re-elaborates on the design issues from a domain-neutral viewpoint.

The third paper, contributed by *Jože Tavčar*, *Jože Duhovnik* and *Imre Horváth*, presents the results of a comprehensive survey of the validation approaches and methodologies of cyber-physical systems of varying adaptability capabilities. Entitled '*From Validation of Medical Devices towards Validation of Adaptive Cyber-Physical Systems*', the paper starts out from the traditional frameworks of system validation in the development phase and arrives at the dilemmas of self-validation of adapted functionalities, architectures and/or behaviours at run-time. Traditionally, validation is based on a predictive analysis or simulation of the designed operation. However, smart cyber-physical systems (S-CPSs) self-manage their operation and architecture with respect to the overall performance objectives and the environmental effects. The authors claim that this type of systems, which adapt at run-time and evolve over time, cannot be validated by the conventional (deterministic) approaches. They took smart CPSs used as instrumentation in the medical field as an example. They found that the dedicated run-time self-validation methodologies are still rather scarce in the literature, even in the case of adaptive software systems. As a solution, the propose a procedural framework, which includes checklists-based validation of: (i) the designed constituents and features of the system, (ii) comprehensive risk assessment, (iii) checking the interoperation of the sub-systems and constituents, (iv) creation of a validation plan with regards to the run-time operation control capabilities, (v) execution of validation, and (vi) making corrective actions and reporting before launching the system. They also suggest that the tasks of operational and behavioural validation should be shared among the system designers and the designed systems. Designers need prognostic approaches, while systems should be able to validate their run-time generated adaptation plans and execute them run-time.

The fourth paper, contributed by *Jan van Niekerk* and *Elizabeth Ehlers* under the title: '*CESIMAS: A self-adaptive MAS toward improved critical infrastructure protection*', explores the affordances of multi-agent structures in the context of system adaptation. Their starting point is that there is a critical infrastructure (a set of electronic assets) at the core of every organisation that allows them to perform their daily operations and that needs advanced protection. Conventional defender mechanisms have failed to ensure effective protection, partially due to the dynamics of the operational states of the critical environments. There is a need for more adaptive protection solutions, which are geared towards the critical infrastructure. As a possible solution, the authors propose the CESIMAS, which is a continual evaluative self-aware immune-inspired multi-agent system model for critical information infrastructure protection. An artificial immune system uses analogies between the elements and processes of the human immune system and a computational environment. The CESIMAS model supports both preventive and reactive operation, and defines the protection functionality in the proactive, preventive, reactive and responsive dimensions. It allows software agents to adapt their behaviour to varying internal and external stimuli. This way, the agents establish a self-aware and self-adaptive multi-agent system, which enables more effective responses and a higher level protection. The model was used in the prototype implementation of a critical infrastructure protection system as a virtual environment. Prior to the deployment of the model, self-set data were used in the agent training process.

Submitted by *Alain-J. Fougères* and *Egon Ostrosi*, the fifth paper focuses on the utilization of a particular type of agents, namely holonic fuzzy agents, as enablers of adaptation of manufacturing equipment. Entitled '*Holonic fuzzy agents for integrated CAD product and adaptive manufacturing cell formation*', the article regards cloud-based design and manufacturing as a dynamic service-oriented network. Modelled by a set of holonic agents and defined from a set of holonic feature agents, 3D feature-based CAD-modelled products can be manufactured in virtual digital cells of this network under certain constraints. A holon in itself is a system composed of interrelated semi-autonomous, structurally hierarchic subsystems. The authors also use the concept of attractors, which are a stable product/workcenter or a stable group of products/workcenters toward which a manufacturing cell formation tends to evolve. The concepts of holon and attractor allow multi-scale cell formation that in turn overcomes the lack of adaptivity of traditional cell formation. One of the objectives of the authors is to capture the uncertainty associated with modelling of the face-feature-product-workcenter-cell network and to provide the needed adaptivity of the virtual manufacturing cell by holonic fuzzy agents. A principle of adaptive formation of virtual manufacturing cell in cloud-based design and manufacturing is also proposed by the authors. They evaluated the capabilities and adaptive capacity of distributed resources in cloud manufacturing according to a scenario, which included different changes in workcenter availability and adding new products that needed reconfiguration of the holonic structure. The fuzzy cell holons are claimed to be capable to overcome the continuous-discontinuous distinction of traditional cell formation problem by relying on a communication network.

The sixth paper, '*Personalized messaging based on dynamic context assessment: Application in an informing cyber-physical system*', is based on the research of *Yongzhe Li*, *Imre Horváth* and *Zoltán Rusák*. Hazard-intense applications of cyber-physical systems (CPSs) such as evacuation of a building-in-fire requires optimal management of the concerned human individuals. The authors' hypothesis was that a CPS can collect information about the actual situations and can generate information in a situation-adaptive and time-effective manner. Personalized messages are tailored to the individual situation of people and communicated through their mobile devices. Dynamic context processing, decision making, and informing stakeholders was found as a complicated research and engineering challenge. As a solution for the latter, a personalized multi-message construction mechanism (MCM) was designed and implemented. It is enabled by computational algorithms for dynamic context modelling, inferring and reasoning, and message synthesis. The basis of generating messages is a quantitative evaluation of the implications of the relevant situations with regards to the target stakeholders. The concept of impact indicator was used to represent the implications of situations and a personal danger level indicator was used to choose a proper message template for message construction. The algorithms included in the MCM were validated in a (simulated) indoor fire evacuation guiding application. Test people were involved in the practical evaluation of the quality of the generated messages. The conclusion is that the proposed MCM provides more sufficient information about personal context and expected actions than the messages constructed based on static context information.

The seventh article is entitled '*Simulating human strategic vision in real-time strategy games with holonic superposition intelligent multi-agent systems*', revisits the issues of system holism and system intelligence. Completed by *Gerard Gouws* and *Elizabeth Ehlers*, the work presented in this article builds on the Real-time Autonomous Superposition Strategy Arena platform, abbreviated as Ripsaw. The starting point of the authors is that simulating human-like long-term (strategic) vision in real-time strategy (RTS) games is challenging. Ripsaw is used to facilitate the participation of autonomous players in an RTS game. The authors used Ripsaw to simulate human-like strategic intelligence in RTS games by incorporating the concept of holonic superposition intelligence. Ripsaw also helped avoid repetitive artificial behaviour that often leads to predictable and exploitable predicaments when facing human players. Another enabler used by the authors is the Holonic Superposition Collaborative Multi-Agent Systems Architecture, referred to as Splinter. This realizes holonic superposition intelligence by incorporating the linear quantum superposition principle, the concept of holonic multi-agent systems, and the beliefs-desires-intentions (BDI) model. By doing so, it facilitates attaining behaviourally adaptive intelligence in Ripsaw. In addition to the generic architecture of Ripsaw and the fundamental and theoretical cornerstones of Splinter, the paper discusses an experiment, which demonstrates the results that Ripsaw could produce at simulating human-like strategic vision. In the experimental game, artificial competitors with differing human-like strategic visions were competing. This research exemplifies a promising approach to simulate human-like strategic vision in self-adaptive systems through incorporating holonic superposition intelligence by gamification.

The eighth paper, entitled '*Development of behavioural modules for mechatronic product families using the 3D design structure matrix approach*', addresses the issue of adaptation of product development strategies to the changing needs of customers. Contributed by *Zuhal Erden*, the article reconfirms that adopting mass customization (diversity in product ranges) requires designing modular products. Modularity of products can be achieved via platform-based systems, in which combinations of various modules are assembled using a common platform. Though an intense research in modularity of mechanical products reported in the literature, the research on modularity of smart systems, such as advanced mechatronic products, is quite limited. Thus, the objective of the presented work was to develop fundamental behavioural modules to facilitate the systematic design of platform-based mechatronic product families for mass customization. Towards this goal, the well-known concept of design structure matrix (DSM) was adopted. It extended to form a 3D block defined by the dimensions of (i) sensorial, (ii) motoric and (iii) cognitive behaviours. Using the modified form of DSM, various fundamental mechatronic behaviour modules were developed. The author applied symbolic representations at the specification of the mechatronic behaviour modules, which were further detailed by using state-event modelling at the early stage of design. The developed modules can enable behavioural adaptation of smart systems through a systematic formal structure. The sensorial, motoric and cognitive behaviours are to be specified according to the intended robot tasks. Some mechatronic behaviour modules have been implemented in this study to demonstrate a specific task-oriented robot family composed of (i) guide robots for museums and shopping malls, (ii) a guard robot, (iii) a house-cleaning robot and (iv) companion robots for children, the elderly and pets.

8. Conclusions

Every paper included in this special issue contributes either to the understanding or to the

Table 1. A bird-eye overview of the articles included in the special issue

Nr.	Authors	Paper title	Main contribution
2	Stefano Borgo*	Components and Interactions: Paving the Way to Model Agent-Based Cyber-Physical Social Systems	Characterization of the class of agent-based adaptive cyber-physical social systems and development of an ontological framework based on the traditional notions of component and
3	Jože Tavčar* Jože Duhovnik Imre Horváth	From Validation of Medical Devices towards Validation of Adaptive Cyber-Physical Systems	A multi-step process framework for validation of smart cyber-physical systems for reliable and safe operations and adaptation in the design phase
4	Jan van Niekerk* Elizabeth Ehlers	CESIMAS: A Continual Evaluative Self-aware Immune-inspired Multi Agent Critical Information Infrastructure Protection System Model	Establishing a natural analogy-based adaptive model, testing its capabilities through a laboratory prototype, and implementation of a dedicated agent training process
5	Alain-J. Fougères* Egon Ostrosi	Holonic Fuzzy Agents for Integrated CAD Product and Adaptive Manufacturing Cell Formation	Capturing the uncertainty associated with modelling of a face-feature-product-workcenter-cell network and providing the needed adaptivity by holonic fuzzy agents
6	Yongzhe Li* Imre Horváth Zoltán Rusák	Personalized Messaging based on Dynamic Context Assessment: Application in an Informing Cyber-Physical System	Using dynamic context information representation and inferring as the basis of situation-adaptive generation of messages for humans involved in critical simulations
7	Gerard Gouws* Elizabeth Ehlers	Simulating Human Strategic Vision in Real-Time Strategy Games with Holonic Superposition Intelligent Multi-Agent Systems	Exemplifying a promising approach to including human-like strategic vision in self-adaptive systems through incorporating holonic superposition intelligence by gamification
8	Zuhal Erden*	Development of Behavioral Modules for Mechatronic Product Families using the 3D Design Structure Matrix Approach	The proposed concept of behavioural modules not only supports modular design of smart systems, but also their self-adaptation to varying operational conditions

implementation of behaviourally adaptive engineered systems. As far as understanding is concerned, the surveys summarised in the Extended editorial and included in some of the technical papers casted light not only on the broadening spectrum of adaptive functionalities and features of various systems, but also on the very fast development and the immense amount of knowledge generated. To be aware of all of these is becoming every day more and more challenging for system engineering researchers and system engineers. Based on the content of this Special issue, a reasonably articulated insight in the run-time behaviour and adaptation of complex systems can be obtained. One important contribution is typifying adaptive systems according to their capabilities. Namely, if the run-time activity of a system is the enactment of a set of hard-coded actions (selected and/or configured according to the operative context), then it is a Type I adaptive system. If the system is equipped with a set of pre-defined strategies (each strategy is an aggregation of actions) and if the strategy is selected and/or configured at run-time according to the state and objectives, then it is a Type II adaptive system. If a system is able to infer and assemble a new strategy for operation, architecture and behaviour at run-time, then it is Type III adaptive system. Finally, if a system can creatively modify its run-time models towards novel behaviours and services based on dynamically generated operational, architectural and behavioural patterns, then it is a Type IV adaptive system. In the order of mention, these types reflect higher level of system intelligence and sophistication of resource management. As a takeaway, Table 2 gives a concise overview of the papers included in the special issue and exposes their main contributions.

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