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Historical Survey and Emerging Challenges of Manufacturing Automation Modeling and Control: a Systems Architecting perspective.

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Abstract: An architecting perspective is derived as part of a more global perspective, related to manufacturing automation modeling and control through four industrial revolutions. This historical survey (Pereira et al., 2017) highlights the impact of digitalization both on isolated machines and devices, and on the architecting of large-scale manufacturing and logistics systems. To distribute the holistic control over related components, two main paradigms have been followed for the engineering of those System of Systems (SoS): (1) technology-enhanced, and (2) bio-inspired. In both, the cognitive orchestration of the knowledge and skills involved in a system project remains challenging for the interdisciplinary togetherness and harmony required beyond the disciplinary boundaries. Finally, lessons learned, as well as acquired knowledge through this innovative history are addressed with several open questions and emerging challenges related to the cyber-physical systems evolution.

Keywords: Holistic Control; Logistics; Knowledge Orchestration; Systems Engineering; System of Systems Control.

1. Introduction and Context

A historical survey of the “Factory of Future [1]” paradigm over time points out a recurrent search of “system in the loop” manufacturing enterprise control aligned with the increasing “hardware-software in the loop” capabilities of automation technology. This systemic perspective is characterizing the integration-in-manufacturing and the intelligence-in-manufacturing paradigms which intricately have been sharing this common thread over the past forty years under industry-led initiatives (Boland et al., 2001). Two different architectural patterns of control can be identified in meeting the systemic purpose of product-service expected symbiosis:

- Centralized/hierarchical approaches, resulting in the well-established technology-enhanced Computer Integrated Manufacturing for Enterprise-Control System Integration issues;
- Distributed/heterarchical approaches, resulting in certain promising biology-inspired generation of Intelligent Manufacturing Systems for Enterprise-Control System Openness issues.

Large-scale manufacturing and logistics systems exhibit properties (Figure 1, left) characterizing System of Systems (SoS) behaviors interoperating both as parts and wholes for a period of time, while sharing a common purpose. The compelling challenges (Figure 2, Monostori et al., 2015) raise issues on advantages and disadvantages relating to the balance of these characteristics (Figure 1, right) -- between automation and Human in the control loop (Figure 5, chapter 10, Millot et al., Boy, 2011), and between system architecting alternatives:

- Beyond closed change, suggesting control and Integration (manufacturing system and its multiple related typology);
- To meet open-ended change, suggesting openness and distribution (extended production system);
- Under contained change, suggesting engineering management of both (adapted from Brier et al., 2004).

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The long-time search of manufacturing systems automation and modeling at large scale has been recently termed *öDesign for Resilience* by Reyes Levalle and Nof (2017), as well as *öDesign for the Unexpected* by Valckenaers and Van Brussel (2017). The objective is to better prepare effective responses ahead of time (by design) to future uncertainty, which too often is revealed a posteriori in real operation by systemic failures (Boardman and Sauser, 2013).

Architectural patterns are discussed in more detail in sections 2 and 3. The reality/knowledge illustration aims to suggest some partition between the technology-based deductive architecting process in reality, and the model-based inductive architecting process in knowledge (Maier and Rehtin, 2009) before synthesis with regard to a system perspective. Therefore, section 4 explores their interdisciplinary necessary coupling $\rightleftarrows$ as a complete knowledge-based architecting process to encode/decode (Figure 5, Rosen, 2012) a responding control system (Figure 3.1, Lawson, 2015) to a situation with certain technology.

Finally, from this synthesis of lessons learned, and of the acquired knowledge from these return-of-experiences, section 5 concludes with a possible regeneration of the scientific corpus in order to explore what is at stake with respect to the cyber-physical and sustainability challenging paradigms.

Figure 1: Manufacturing Enterprise System of Systems

2. Integrated Manufacturing Systems and Engineering

With the emergence of computer communications and personal computers, in the 1980s, the industrial manufacturing automation community initiated the development of Computer-Integrated Manufacturing (CIM) systems. Integration in Manufacturing has been a first systemic paradigm, aiming to organize Humans and Advanced Manufacturing Technologies as a whole system. The integration was meant not only at the field level, but also at the management and corporate levels, resulting in a centralized/hierarchical architecture (Mesarovic et al., 1970) around an information system backbone (Figure 2, right).

2.1. Component-based integrated-system architecting

A host of data-intensive components are achieving to network, step-by-step, the entire integration of Manufacturing Plant Control within the overall control of an Extended Enterprise System. Eventually, such networking has been accomplished virtually.

Progress in real-time communications (Neumann, Morel et al., 2007), web-enabled and wireless technologies have strengthened the two-dimensional integration of automation in order to manage the customized manufacturing of both goods and services, as desired by the Internet society for agile Business-to-Manufacturing (B2M) and Business-to-Business (B2B) purposes:

- Synchronic, in time, integration of shop-floor process controls into plant-wide information management systems,
- Diachronic, through time, integration of Product Life-cycle Management over the manufacturing chain.

Many competing technologies for Factory Automation (Figure 2, left) have inferred a complication of the operational system architecture, both in terms of heterogeneous material means (dedicated computers, communications networks, supply chain operations, etc.) and in terms of the software functions (scheduling, control, supervisory control, monitoring, diagnosis, reconfiguration, etc.) it embeds. To address these increasing technological and functional interoperability issues, many efforts are being deployed to design architectures that are more flexible, by federating intra- and inter- zones of hardware/software facilities which share a common purpose (Business, Security, Logistics, etc.)

Enterprise modeling frameworks have been proposed (Zachman, 1987) in order to functionally cope with the complexity to engineer these complicated Enterprise systems by defining modeling rules and generic infrastructure to be instantiated. The ISO 15439 Enterprise integration Framework for enterprise modeling resulted from the 1990s of world-wide joint works of IFAC and IFIP as well as international R&D programs leading to CIMOSA [Computer Integrated Manufacturing Open System Architecture] (Vernadat, 1993) and GERAM [Generalised Enterprise Reference Architecture and Methodology] (Nell, 1997). The Purdue Enterprise Architecture Framework (Williams, 1994) has been first a standardized reference for Business-to-Manufacturing plant-control functional integration issues relating to Batch, and Continuous as well as Discrete Processes. This framework (Figure 2.1, Williams, Nof 2009) remains the standardized backbone of the set of modeling techniques (Figure 3, Brandl, 2016) simplifying the federation of components systems for factory automation [2].

Figure 2: Multi-dimensional component-based architecting

2.2. Service-oriented integrated-system architecting

Service orientation architecting (SOA) has intensified in the 21st century. It was motivated by the scale-up trend in manufacturing that cannot just add more ICT (Information Communication Technology) agents, virtual and augmented reality devices and processes (Figure 3, left). There is the evident need to integrate their use for collaborative services to support new, distributed and complex architectures that comply with the convergence to sustainable production modes. Sustainable production, manufacturing, and logistics require interactions and mutual support among multiple virtual and physical facilities, enabling sustainable, efficient

and cost-effective operations based on rich computational and cyber-collaborative autonomous points of view (Moghaddam and Nof, 2017; Vernadat et al., 2018). The emerging SOA concept (Figure 3, right) is a change in distributed and collaborative architectures, towards a distributed set of cyber-physical entities with service orientation: enhanced cells, startup organizations, and other production and supply sources, all with defined identity and purpose, and capability to collaboratively combine different processes as "services-components" (Moghaddam and Nof, 2018). This service orientation is envisaged as a complete symbiosis between services and products (Silva and Nof, 2015; Dutra and Silva, 2016; Moghaddam et al., 2016; Moghaddam and Nof, 2018; Postigo et al., 2018). The emergence of manufacturing service orientation in the architecting perspective (Figure 4, left) has advanced, following beneficial trends in the digital and cyber-physical convergence (Schmenner, 2009; Tao et al., 2011; Nof, 2013; Devadasan et al., 2013; Nof and Silva, 2018; [4]). A recent review of smart manufacturing architectures (Moghaddam et al., 2018) has pointed out the convergence of manufacturing and industrial reference architectures and international standards towards service orientation, based on its advantages (IBM, 2008; Li et al., 2010; Gao et al., 2011; Jiang et al., 2016; [5]).

Figure 3: Multi-dimensional service-oriented architecting

2.3. Synthesis

Both for CIM and SOA, formal ontologies (Figure 4, left) under standardization aim to provide guidelines to solutions by addressing the structural perspective of an architecting process. Therefore, Process Modeling Techniques [3] must complete the dynamics of the overall Enterprise system architecting process (Figure 4, right) in order to functionally depict workflows in form of sequences of business activities before their mapping onto organizational units and operational components. All these modeling techniques (Panetto, 2007) reflect basically an integrative approach, despite some systemic traits, such as the enterprise system life-cycle.

These works and other complementary ones have not fully taken up the challenge of engineering an Enterprise System as a whole, while contributing, among others, to world-wide technology such as the well-known ERP. Even though the roots of this approach can be traced to manufacturing relative to Taylorism, the scientific basis of these process-based frameworks and techniques came from another community; those aware of relational data management, and information systems modeling, rather than automation engineering. The main drawback was that information-based process modeling, or workflow modeling, may entail more feedbacks than those constrained by the physics of the operational processes to be controlled in real-time. The resulting enterprise system architecting gap is that the information bridge between the operational and management enterprise levels is not fully integrated, despite the data bridge of the Manufacturing Execution System technology. The expected Enterprise control system is a large puzzle of networked automatons based on legacy or de-facto standardized, as well as proprietary hardware and software parts. The

overall behavior of which is more or less well-managed, yet failing to be wholly contained. The mature pyramid remained the prevailing 2-dimension integrative approach, even with more or less digitalized technology. Information Control Problems in Manufacturing are still reflecting some lack of systems engineering knowledge by differentiating component-based bottom-up from system-based top-down integration to efficiently cope with the increasing overlapping of hardware, Software, and Humans, interacting in the control loop.

Note that the evolution from Enterprise-control synchronic-integration to diachronic-integration is impacting the system togetherness and harmony which is expected to be ensured by a web of multiple, interacting data conduits. In return, Enterprise systems are accumulating so much big data relative to product variety (Giovannini., 2015) that key milestones in the evolution of dependability in manufacturing plant control pointed out the threat that software growth may limit further automation progress for the entire enterprise system (Figure 4, Johnson, Morel, et al., 2007), with an ecological cost related to increasing use of data servers.

Figure 4: Two systemic perspectives of enterprise architecting frameworks

3. Intelligent Manufacturing Systems and Engineering

As argued by Monostori et al. (2015), integration-in-manufacturing often resulted in rigid, centralized or hierarchical control architectures, even if computerized, which could not cope with a changing and uncertain manufacturing environment. Thus, distribution relates to cooperative control architectures with more or less autonomous agents, ensuring local control and wholly interoperability are necessary to ensure certain collective, holistic goals. For instance, design for better responsiveness to open-ended changes, which is required by the mechatronic society. Transitioning from integrated to distributed automation for product life-cycle issues has been strengthened by the considerable amount of interest - occasionally converging or controversial - relating to integrating/distributing a form of technical intelligence into control architectures. Two complementary threads have been explored relating to the shifting intelligence-in-manufacturing paradigm:

Computational agents architectures -- embedding more computational techniques into automation agents from the upper to the field level, to achieve numerical control while enabling interactivity among participating entities, including interactions with Human agents. Early techniques for intelligent control have been associated to Artificial Intelligence, for example, to develop a unifying Cell Management Language for Factory Automation (Wright, 1988) and for diagnostic expert systems. They are in general applied in manufacturing and process automation in order to deal with well-defined or imperfect knowledge depending on domain local control goals (Figure 1, Zaremba et al., 2003). They are currently associated to computational decision-making (Dolgui and Proth, 2010; Filip et al., 2017) in order to distribute some parts of the overall control on networked units for a wide-

range of applications, such as model-based predictive control (Figure 12, Monostori et al., 2015). The system architecting process remains limited to the reducible ÷divide-and-conquer÷ principle, even if applied to more cooperative control.

Bio-inspired architectures -- On the other hand, embedding certain level of technical intelligence beyond computational techniques led the IMS community, envisions new distributed automation paradigms by designing bio-inspired architectures. The related form of technical intelligence advances beyond simple data through information to knowledge to be also partly embedded not only into intelligent components, but into the products themselves. Thus, products and devices can interact together as an intelligent system by means of remote communication, e.g., machine communication protocols, and Industrial Internet of Things. Continuing roadmaps have aimed at defining the desired structure of the factory of the twenty-first century since the world-wide industry-led IMS initiative arguing that manufacturing technology as a whole has not been systematized in any demonstrable or explainable form (Yoshikawa, 1995). Two main bio-inspired paradigms are MAS (Multi-Agent System) and HMS (Holonc Manufacturing System). Their purpose is to contribute to the IMS systemic search to reflect ÷on the fly÷ the surrounding world-of-interest. With these two paradigms, any so-called system must service by exhibiting behavior in actual reality, and by generating meaning in knowledge without which the participating individual components cannot achieve the collaborative systems goals.

3.1. Agent-based intelligent-system architecting

The *product-driven control paradigm* is a major contribution to the full observability of flowing agents by embedding automatic-identification technology [AUTO-ID]. Discrete-Event Control deals currently with theoretical modeling techniques applied to formally define, even to automatically synthesize, the (unknown) control rules from both the (known) dynamics and (known) goal that an automation system must achieve in a specified time according to: $\{\text{Process Dynamics} \wedge \text{Control rules} \supset \text{Goal}\}$ (Fusaoka et al. 1983). These dynamics are resulting from sensing processes triggered by a flowing discrete object through actuation processes in order to close the control loop for the shape, space and time operations to which a product is subject during its life cycle. Embedding AUTO-ID led to formally revisiting the full observability of the (discrete-event) state space for direct product sensing, rather than inferring indirectly from process dynamics as it is usually done (Figure 5, right) according to: $\{\{\text{Product} \wedge \text{Process}\} \text{ Dynamics} \wedge \text{Control rules} \supset \text{Goal}\}$. Continuing efforts [6] towards the Internet of Things pointed out the pivotal role of the flowing interactive products to trigger the holistic dynamics of a responsive automation system in a wide range of industrial applications related to the concept of ÷intelligent products÷ (Figures 1 and 2, Leitaó et al., 2015). They have contributed to anticipate the symbiosis between the tangible flow of goods, and the non-tangible flow of the related services; by breaking off the control hierarchy, they enable an ÷intelligent product÷ (Baina, 2006) to actively participate as control agent of the manufacturing enterprise resources (Figure 5, left).

Figure 5: AUTO-ID based product-driven control paradigm

The *PHM paradigm [Prognostics and Health Management]* results also from a multidisciplinary, integrative approach of embedding accurate algorithms into control units. By applying such algorithms at any enterprise-system level, it is possible to improve the precision of customized information in assessing systems in complex situations. The Watchdog agentsTM infotronics-based approach (Djurdjanovic et al., 2003) is becoming technologically mature [7] to move from traditional failures, and predict and prevent by industrial maintenance practices for cost-oriented automation (Erbe, 2005). Beyond technology, the deployment of such intelligent maintenance systems (Lung et al., 2009) relates also to IT BPM best practices (Léger and Morel, 2001). The objective is to architect together a set of techniques and tools for enabling the prognosis when performance is becoming unacceptable, the diagnostic of why the performance is degrading, and the decision as to what maintenance action to perform. It also includes the performance benchmarking resulting from cumulative learning (machine learning) based on previous, similar operating processes. Data-driven and model-based prognostics can be combined with Knowledge-based Management technique in order to enable the maintainability of a targeted system-of-interest in operational conditions (Chen and Nof, 2012; Regal and Pereira, 2014). Relevant properties-of-interest to be observed in-situ can be predicted a priori from relating instantiated ontology, encapsulating the knowledge gained from previous experiments (Figure 6, right). Relevant data-of-interest are thus embedded into a computer platform in order to be checked for remote maintenance operation reflecting in real-time the related situation system (Figure 6, left). Note the instantiation process (Figure 6, middle) which enables the coupling relationship between reality and generic knowledge, as detailed in section 4.3.

Figure 6: Coupling between remote PHM-IT infrastructure and IMS Engineering (courtesy of www.Predict.fr)

The bio-inspired *MAS paradigm* advances further to implement agent-based intelligent systems by bringing a computing technology for dynamics control issues as a set of interacting software agent exhibiting properties of autonomy, social ability, reactivity, proactiveness (Wooldridge, 2002). Designing a MAS is both concerned by the agent design, such as the Beliefs-Desires-Intentions model (Rao and Georgeff, 1995) and about the society design as for Manufacturing Systems applications. Stimerger (Grassé, 1959), mimicking that an insect does not direct its work, but it is guided by its work, is one of the mechanisms among many others, which has been explored in the field of swarm intelligence to indirectly coordinate, through the environment, the trace left by an operating agent to cooperate with others. The principle is that the traces left in the environment by actions stimulate related close actions by the same or a different agent. In that way, subsequent actions tend to reinforce performance and build on each other, leading to the spontaneous emergence of coherent, apparently systematic activity. The resulting network of autonomous, yet interacting reasoning elements, enables to dynamically and adaptively architect complex distributed systems without localized decision-making processes. Nevertheless, the overall system performance at the right scale of manufacturing applications can be only assessed by simulation as evidenced by the multitude of experiments (Figure 1, Leitao et al., 2013). The lack of a consensual MAS engineering framework (Marik et al., 2005; Vrba et al., 2011) is another limitation to meeting system readiness level [8] in reality. This limitation is added on top of industry's uncertainty whether emerging behaviors (Figure 3, Monostori et al., 2015) can be contained to holistically target control goals, while being grounded to the plant physical level.

3.2. *Holon-based intelligent-system architecting*

The focus of component-based approaches, modeled by cooperative agents that operate as a whole artefact, may not be sufficient to satisfy a contextualized mission that can overcome open-ended changes in future, unexpected situations.

Pioneering works on science and engineering of intelligent systems led to the basic structure of the Real-Time Control System Architecture (RCS). RCS aims to integrate various intelligent techniques in order to bridge the gap between *deliberative* and *reactive* controllers. The fundamental structure of a control loop (Figure 1, Albus 1991) of the overall hierarchical architecture combines real-time sensory perception (SP) with prior information. The purpose is to reflect a model of the world-of-interest (WM) for behavioral (BG) knowledge-valued (VJ) decision-making in automation contexts. In particular, it aims to handle uncertain and unstructured operating environments with the 4D/RCS extension adding time as another dimension. Among many application domains, the ISAM (Intelligent System Architecture for Manufacturing) engineering framework (Figure 14, in [9]) is an RCS application in the Manufacturing domain, which consists of three hierarchically layered sets: behavioural, computational and organizational processing nodes, organized as a nested series of control loops. Despite possible computer performance issues to reflect WM in real-time with regard to situation system, the three fundamental reflections on what is matter-energy; what is life; and what is mind should remain relevant for any generation of IMS. They have inspired the progress discussed next on distributed intelligent automation.

The works on the *HMS paradigm* are combining a vision related both to intelligent beings and intelligent agents. They are designed to tackle expected heterarchical control issues. The holonic concept originated from the work of Koestler (1967) who termed Holon the hybrid nature of organization units in biological and social systems. These units behave *partly* {h} as dependent parts and *wholly* {H} as self-contained wholes according to the way you consider them. The relating open-ended hierarchy was termed holarchy, since the architecture is comprised of holons and is not bounded in either downward or upward directions. Thus, autonomy of communicating agents cooperating in a decentralized manner to meet holistic objectives must be under coordination to contain the so-called emergence constrained in real-time practice by physical relationships. The HMS computational features equip MAS through time as a suitable technology for implementation (Babiceanu et al., 2006). A key difference is the part-whole aggregation of entities, encapsulating both software and hardware building blocks (Figure 7, right) to cope with the large-scale two-dimensional changes that are dynamically affecting an entire B2M2B (Business to Manufacturing to Business) chain. The holonic control theoretical framework has inspired the community of Manufacturing and Logistics Systems since its inception. The related PROSA (Figure 7, left), standing for {Product-Resource-Order-Staff Architecture}, is a prominent experiment from the early 1990s (Van Brussel, 1998), via PROSA-DMAS, to ARTI (Valckenaers 2018). The reference holarchy is composed of recursive agents to be instantiated for specific manufacturing applications. A key system property is to reflect on the fly the behavior of a related real-world {Resource Holon} by processing relevant data with other Holons, in order to maintain its local control objective requested by {Order Holon} when executing the operational tasks of a {Product Holon}. Note the separation of concerns of each of the three basic (above) Holons. Each of which can aggregate supervisor holons according to the specific underlying domain; and an optional {Staff Holon} with advisory role, which can be adapted when facing unexpected situations. To cope with scale up and edge effects of combinatorial data explosion, and for short-term forecasting and predicting unexpected events, the associated DMAS, ({Delegate Multi Agent System}) has been designed. It refers to a coordination mechanism of the dynamics of the HMS, which is needed to support Holons to fulfil their task responsibilities with a swarm of ants-like for feasibility, exploration, and intention. The approach has been recently revisited (Valckenaers and Van Brussel, 2017) to consider architectural design guidelines based on Laws of Artificial (Simon, 1969) and on relevant insights about complex-adaptive systems (Waldrop, 1993). Despite this effort, a wide range of laboratory experiments focused mainly on MAS technology to deploy *Intelligent Agents* based platforms. These experiments have focused on how the system knowledge corpus can handle dynamic changes, rather than on how to mirror the reality of a targeted world-of-interest. PROSA-related efforts for industry adoption (e.g. in the automated warehousing domain) at the higher TRL levels [8] are not using agent technology but Erlang/OTP, a technology from the telecom industry whose scalability is suitable for embedded systems. That approach may be a prerequisite property for any service oriented architecture and standards. The objective would be to plug-in, on the fly, executable models reflecting open changes of a situation system, such as IOT (Internet of Things) based changes. However, addressing the coupling between reality and a related IT architecture requires to reverse some of the current industrial practices. Thus, ARTI ({Activity-Resource-Type-Instance}), (Figure 7, middle), revisits PROSA to cover application domains beyond manufacturing. The approach emphasizes a generic nature, aimed at building an IT platform based on *Intelligent Beings* as activity performers accessing reality through (and not from) their digital twins as *Intelligent Agents* (Valckenaers, 2018).

Figure 7: Holonic Manufacturing System-of-Systems Architecting

3.3. Synthesis

An archetypical shift for distributed automation has been initiated by continuous process industry-led R&D [10][11] in the late 1980s from the technological opportunity to unify a continuum of data communication around a real-time fieldbus (Thomesse, 1998). An important architectural pattern has then resulted from a wide-large European R&D program as an integrated control, maintenance, and technical management system [CMMS] allocating intelligent actuation and measurement functions [IAMS] to distributed intelligent actuators and sensors (Figure 6, Pétin et al., 1998). Digital technology can now encapsulate the matter-energy flow through a data-driven channel, not only between technical objects, but also with human agents whose interacting capabilities are augmented. The related overall digitalized interaction is normalized by a service channel to enable human operators access to information anywhere, at any time (Figure 15, Dobre, 2010a) as addressed by on-going R&D [12] for nuclear power industry instrumentation and control (Figure 11). Note that these works have explored over time some aspects of the matter-energy, physico-physiological and data-information interactions between CMMS/IAMS agents (Bouffaron et al., 2014).

Compared with the discrete process domain, the product-driven paradigm contributed to ensure the diachronic flow of both services and goods (McFarlane et al., 2013) in the manner of matter-energy in the continuous process domain, by means of a digitally-active flowing object. Thus, it raised a question on the form-space-time partition between planning and control in manufacturing and logistics systems. In addition, it sought to envision with an energy perspective (Dembale et al., 1994) how to ensure togetherness and harmony of the interactions in the related, digitalized system of systems (Koubeissi, 2015).

In both area, the meaning of ‘intelligence’ must be interpreted as based on the designer’s knowledge, embedded into digital agents. Embedding is designed by means of computational technology (Dobre, 2010), to reflect the reality of a given world-of-interest, in which the targeted system-of-interest has to behave, operate, and achieve its purposes.

The relative immaturity of IMS experiments for the next generation of manufacturing systems can be overcome by the relatively powerful holistic approach of the holonic control paradigm for facing resilience issues of large-scale SoS. It can be applied towards a broader range of applications, such as recently addressed by (Figure 4, Le Mortellec et al., 2013) for Holonic Diagnosis of a train system. That makes a ‘holon’ in particular a knowledge building block of the system’s DNA (Boardman, et al., 2009a) to recursively define a SoS at multi-scale as a holarchy {H, h}. Note that this holonification should be built from a real situation awareness by a sentient being {h} (Wilber, Mella 2009) requiring certain wholeness to bound a limited part of reality it is

perceiving complex at that time (Kuras, 2006). Additionally, next generation manufacturing systems design should be explored more extensively at another engineering time for designating a situation system (Mayer, 2018), and overcoming errors and conflicts in complex interactions among agents and holons, by the design principles of Collaborative Control Theory, CCT (Nof, 2007; Nof et al., 2015).

4. Interdisciplinary Systems Engineering

System, as conceptualization unit of reality of a situation perceived as complex (Pénalva, 1997), is suggesting a required wholeness to cope with some hidden aspects occurring between related interacting parts in reality and in knowledge. The respondent architected whole is a result of a system engineering process. In this process, the related body of interdisciplinary system knowledge is a prerequisite to cope with the hybrid nature of the physico-physiologico-artefactual interactions to be controlled in operation. Thus, harmonizing by orchestrating together the individual disciplinary knowledge and best practices also relates to the cognitive nature of the collaborative system thinking and acting process. Together, they can reconcile the easy-to-use approach of the digital technology with the architecting approach required for manufacturing and logistic system resilience concerns.

4.1. Non-linear Systems Thinking and Acting

The Human role in the control loop is to be aware of a situation and to face the unanticipated in real operation (Boy, 2011). Furthermore, there is the question of what can be automated, or not, or both (Millot et al., Boy 2011; Patton, chapter 18, Nof, 2009). Even if Humans have limitations leading to recurrent errors (not always failures) at work, requiring enabling artefactual control (Galara, 2006), that behavior points out the unique human capability to build by detour (Berthoz, 2012) a cognitive control based on certain embedded knowledge blocks, previously acquired. This property, called simplicity, may be understood as a constitutive process to make the most likely decision by cobbling alternative solutions to complex problems in a given situation. A sensory prerequisite (Lieber, 2013a) is that the artefact affords a right quantity of physical assets for enabling a Human to perceive correctly, before acting accordingly (photon, as quantum of energy, for orange sensory, in Figure 8, left). Paradoxically, this essential property, and human factors in general, are not adequately addressed beyond technology-based enhancements by the manufacturing operation control community, even when targeting resilience issues.

In the engineering domain, a set of artificial modeling principles has been drawn by biologically inspired conceptualizations on what is a system since the early times of Systemics (Bertalanffy, 1968; Pouvreau, 2013). Its relationship to cybernetics (Wiener, 1948; Forrester 1961) remains essential, as addressed in recent works of the worldwide community of Systems Engineering (BKCASE, 2017). It is, therefore, possible to agree that the "whole-part" decoding-encoding relationship of a reality (Rosen, 1991) is not as trivial as currently addressed in disciplinary engineering. It is necessary to inquire about its effectiveness for integrative foundation of any system-centered interdisciplinary engineering. Coping with the related non-formal part of a reality involves system thinker's attitudes (Figure 8, top right). For example, to reassess the uncertainty of what can be patterned in an un-ordered domain, from what is known in the ordered (formal) domain (Kurtz and Snowden, 2003), such as interactions taken implicitly (and mistakenly) as contained by the surrounding environment of a system, when they may actually not be contained by it. For example, what may or may not damage the togetherness and harmony (Boardman and Sauser, 2008) of a whole structure and behavior (Figure 8, bottom right) is of importance for situational assessment to correctly designate the reinforcing and balancing causal loops of a situation system, before the design of a relevant control system. That realization should be explored particularly for indirect connectivity links of IOT-based infrastructures, which must maintain the togetherness and harmony among inter-networked human, physical, and digital entities (Figure 9, left). Togetherness and harmony are essential for integrating tangible and intangible, whole cyber-physical systems, while mirroring, if possible on the fly the dynamics of a related world-of-interest. Thus, the many alternative pathways (Figure 8, right) are challenging the cognitive, collaborative orchestration of the interdisciplinary knowledge togetherness and harmony between the many engineering actors involved along the entire life-cycle stages of a system-of-interest, from its conceptualization to its retirement.

Figure 8: Simplicity giving meaning to Systems Thinking and Acting in a given situation

4.2. Process-Guided versus Model-Based Systems Engineering

A variety of techniques compiled by the Guide to the Systems Engineering Body of Knowledge focus on certain generic principles of a system approach to perform standardized engineering processes [13] in a recursive, iterative, and concurrent manner, according to project templates. The Model-Based Systems Engineering (MBSE) approach aims to contrast with the traditional document-centric approach by replacing the basic project artefact of process to a model for expected system modeling added value. Nevertheless, the tautological MBSE (any engineering process is model-based) does not necessarily consider that "system", as primary informal model of the entire architecting, enables an interdisciplinary reduction of the combinatorial complexity of the related multidisciplinary models of parts.

System thinking knowledge elements can be diagrammed in a form of systemigrams, causal-loop diagrams. The objective is to display the dynamics of a situation system under designation, specially reinforcing and balancing loops to explore ōwhat ifō questions. The holistic completeness of this informal process for system-of-interest definition can be then systematically guided by the ōconceptagonō framework ordering twenty-one system thinking concepts into seven triads (Boardman and al., 2009b). This pragmatic architectural framework highlights that {communication command control} forms together one triad, surrounded by six other ones. This approach results in the alignment of any related disciplinary knowledge, such as automation, with the interdisciplinary knowledge reflecting the required respondent system under modeling. Transitioning this architecting system knowledge to traditional engineering knowledge requires unifying system-oriented modeling languages [14] (Cloutier et al., 2015), or domain-oriented [15] (Retho, 2014). Despite ontological representations efforts for knowledge interoperability (Giovannini et al., 2015a), both process-guided and model-based approaches focus mainly on the technical result of the overall engineering process; while possibly being limited in the ability to draw on human capabilities for heuristic processing (Nugent, 2015).

Technology is emerging which dismantles the silos of traditional systems multidisciplinary engineering. Its purpose is to meet the whole digitalization addressed by the ōdigital twinō paradigm shift. A unique and extensible development platform (Figure 9, right) can fully integrate the cross-discipline modeling, simulation, verification, and business process. Thus, it can significantly enable the exchange and collaborative execution of a set of models, built in their own environments as required by a common system under engineering design. Functional mock-up interface aims to ensure a standardized openness interface to be used in computer simulations to develop complex cyber-physical systems based on off-the-shelf models, even ōon the flyō for some

responsive user-driven control related to IOT-based applications (Figure 9, left). At the same time, however, the increasing range of digital collaboration technologies, albeit useful, are only means to facilitate the cognitive role of a product, project, or team chief in managing the multidisciplinary exchanges of documents, as well as of models.

Figure 9: Technology Enhancing Model Based Systems Engineering (courtesy of 3DEXPERIENCE Dassault Systèmes)

4.3. Interdisciplinary Knowledge Orchestrating

The coupling relationship $\overleftrightarrow{\square}$ points out the feedback that a respondent system has to bind into wholeness relative to a requesting situation system, as recently addressed by Lawson, (2010). It focuses on "why humans make systems?" to cope with a problem or an opportunity occurring in real life (Figure 10).

Figure 10: Cognitive interpretation of the System Coupling Diagram (Lawson, 2010) giving meaning to Interdisciplinary Systems Engineering relative to a given situation system (Dupont et al., 2018)

It also highlights the need for systems to be designed to provide effective and respective services for each other if the whole system of systems is designed to accomplish intelligently its designated collaborative interactions and goals. One of the instantiated system assets is a control element, directing the respondent system mission outputs according to the situation system inputs resulting from operating elements. The interactions of systems and of elements comprise the phenomenological source of requirements measurable properties. Note that the proposed coupling relationships shown in Figure 10 may reason and interpret by interactive exchanges the meaning and implications to dynamically enhance the togetherness and harmony of the respondent interdisciplinary knowledge, relative to the requesting situation system to be controlled. Also note that these mechanisms can be designed by the HUB-CI model of CCT, a virtual hub for collaborative intelligence (Nof et al., 2015). It enables multiple sub-systems to interact, exchange, and learn to improve their interactions by collaborative intelligence and machine learning.

A cognitive interpretation of the overall process consists of orchestrating the appropriate interdisciplinary knowledge into a coherent whole to be allocated { } from the multidisciplinary knowledge assets available in a given project system. The cognitive nature of these coupling relationships has been recently explored by Bouffaron (2016) for interdisciplinary MBSE issues on the basis of the problem frames approach previously addressed for software engineering (Jackson, 1997; Jin, 2006). The proposed heuristics differentiate for each source-sink interaction between a requesting knowledge and the related responding one in order to preserve the individual ability to build by detour (Berthoz, 2014) a model as part of a whole-system model according to the set of predicates:

- Descriptive specification from a domain problem-space according to:

$$\text{Knowledge}_{\text{domain}}^{\text{requesting}}, \text{Interaction}_{\text{source}}^{\text{sink}} \rightarrow \text{Requirement}_{\text{descriptive}}^{\text{problem}} \quad (1)$$

- Prescriptive specification from another domain solution-space according to:

$$\text{Model}_{\text{prescriptive}}^{\text{solution}} \leftarrow \text{Interaction}_{\text{source}}^{\text{sink}}, \text{Knowledge}_{\text{domain}}^{\text{respondent}} \quad (2)$$

- Contractual specification between both domains according to:

$$\text{Knowledge}_{\text{domain}}^{\text{requesting}}, \text{Model}_{\text{prescriptive}}^{\text{solution}} \Vdash \text{Requirement}_{\text{descriptive}}^{\text{problem}} \quad (3)$$

The twin-peaks model-based orchestration process (Hall et al., 2002) results from iterative refinements all along a system project life cycle, between interacting knowledge. Knowledge are, respectively, source of problem-oriented requirements (Equation 1), and sink of solution-oriented models (Equation 2), both being verified (Zaytoon and Riera, 2017) before contractual validation (Equation 3) in silico $\square \Vdash \square$

Technology-enhanced modeling platforms (Figure 9, right) may enable designers to meet TRL proof of the ‘‘right job right’’ (Fanmuy et al., 2012) of the system response to a given situation system, by execution of the multidisciplinary models together. To cope with the difficulty of translating any human intention source into a model for a related human understanding sink, the focus may be to exchange only the essential parts of the interdisciplinary knowledge to be shared. For example, it can be modeled with the de facto-standardized SysML for event-driven orchestration of the multidisciplinary models running in their own working boundaries (Bouffaron, 2016). Note that the validation in situ of the specified situation system control with regard to the perceived reality of a world-of-interest is a non-formal entailment relationship { $\vdash$ instead of $\models$ in equation 3 } between Humans involved respectively in the requesting tangible (operational) domain, and the responding non-tangible (engineering) domain.

4.4. Synthesis

A main advantage of the digital technology is that it can be designed by various suppliers as individual parts, or assets to be cobbled together with relative simplicity, to meet system wholeness. This ‘‘hardware-software in the loop’’ approach may present a possible drawback. It can challenge the ‘‘model-in-the-loop’’ interdisciplinary systems engineering, which aspires to enable collaborating individuals working together (Retho, 2015), even though increasingly better trained with simple-do-it-yourself integrative approaches. At the same time, it is possibly desirable to not collectively frame a ‘‘system-in-the-loop’’ in certain design situations. The orchestration metaphor highlights the ‘‘human-in-the-loop’’ approach by intelligent detour to a synthesis containing the whole system. It is also contextualized in its external environment, and enables analysis of its related internal architecting by investigating relevant component partial solutions (Edson, 2008). From this analysis, artefacts are only considered as means to encompass the

system togetherness and harmony, as required by a given situation. Failing a priori in system thinking for acting, often leads to complicating the design of an essential respondent system by patching a posteriori in-silo digital parts.

Notwithstanding its appropriate use, embedding more digital technology in the architecture may ensure a just-in-time remote continuum of data, information and knowledge flows between plants operated activities, and model-based systems engineering activities. The objective is to enhance complex situation awareness and control on the fly, as addressed by on-going R&D [12] in process industry (Figure 11). More generally, the "Digital Twin" paradigm (Kusiak, 2018) should not mask that it is the tangible relationship between reality and virtuality which maintains any system in its wholeness with certain energy level. Otherwise, digital artefacts may cause user's cognitive overload in real life when facing unexpected system situations.

Figure 11: Towards Operation and Engineering knowledge-driven harmony (Galara et al., 2012)

5. Conclusion and perspectives

The Discrete Process Automation and Modeling community members have been creative and innovative to face the challenging architecting of hardware, software and information in the control loop of large-scale manufacturing and logistics system. It brought together with the computing community a body of knowledge anticipating to certain extent the digital revolution to industry 4.0, (Zuehlke, 2010; Nogueira et al., 2016), and the digital and cyber conversion (Pereira et al., 2017; Nof and Silva, 2018). Its systemic technology-enhanced trait has been to deal over time with the architecting of integrated and intelligent systems related to a wide range of applications and their challenges, such as: shop-floor control; process and planning plant and logistics control; factory, supply chains, and supply networks information and communication networking and integration, SoS interoperability and resilience, and service-oriented issues. The resulting cross-fertilization has addressed through time improvement and management methods as well as heterarchical, interactive and collaborative control design principles. The related innovative traits led, among many, to the well-known ERP technology, as well as to several efficient paradigms such as the Product-driven and PHM ones, Collaborative Control workflow protocols and algorithms, as well as the emerging HMS.

From a historical perspective, despite an impressive production of concepts and experiments, the effectiveness (Nof, 2003) of many architecting paradigms of these technological SoS (Nof et al., 2006) is not yet proven in real work and the Human capabilities have manifestly been insufficiently explored in operation, as well as in interdisciplinary engineering. Several systemic failures and weaknesses are repeatedly reminding us that this corpus of knowledge should be collectively improved, by rethinking beyond technology-enhanced in-silo approaches. To some extent, a complementary trait may be necessary: A symbiotic approach, as suggested by multiple aspects presented the above sections 2 and 3. It may also be possible to consider that the building of an interdisciplinary knowledge, as described in section 4 is one relevant form of symbiosis. The objective is to yield significantly more than just the addition of specialist knowledge which is limited in its ability to reflect the togetherness and harmony of real situations which require full systemic integrative reference.

That realization challenges us to consider better approaches that take into account, in the control loop, the "simplex" domains of human and nature beyond the "causal" nature of man-made artefacts to be able to efficiently cope with cyber-physical (Zhong and Nof, 2015) as well as resilience and sustainability (Moldavska and Welo, 2016; Reyes Levalle, 2018) issues. Understanding and responding to the meaning of "why humans make systems?" may require an earlier (Ponto and Linder, 2011) and faster fundamental shift [16] in education, engineering and service, as people need to be as early as they are primary, secondary and university students; and throughout their career

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Footnotes

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