Industrial Agents as a Key Enabler for Realizing Industrial Cyber-Physical Systems

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Industrial Agents (IA) [1] are multi-agent based systems (MAS) [2] that, for many years, have been advocated as a promising and realistic solution for an emerging set of industrial challenges. The latter, in the past, fell into the scope of enterprise agility [3]–[8] and now, more than ever, pertain to the industrial digital transformation and sustainability spheres. MAS technology is being applied to several industrial applications in the Cyber-Physical Systems (CPS) context, namely in smart production, smart electric grids, smart logistics, and smart healthcare [9]. To understand the future potential of Industrial Agents, one must first have a sufficiently concise view of the past and present efforts, i.e., understand their early applications and current directions. Such a view is seen as a necessity, because over the last decades, the concept of the Industrial Agent has proven to be a bit of a moving target, adjusting to the needs, visions, and technologies of each era. As an example, Figure 1 reflects well this reality, by depicting the most prevalent words in Industrial Agent research papers [10] published by the IEEE Technical Committee on Industrial Agents [11], and makes it evident that they encompass a wide range of industrial system aspects. This work presents a view of the authors, and is driven by looking at past and recent efforts in industrial agent domain, current trends, and relevance with key enabling features of Industrial Cyber-Physical Systems [12,13], in order to assess how the agent definitions, development, and solutions have changed over the years, but also where current efforts may focus.

I. INDUSTRIAL AGENT CONCEPTS

An Industrial Agent means slightly different things to different researchers, and its supporting technologies have been, many times, mixed or confused for the Industrial Agent concept itself, sometimes with detrimental results. The plasticity of the concept has proven to be both its strength and its weakness over the last two decades. Industrial Agent-based systems have been considered in many different domains [9], including Production and Manufacturing [1,14], where the research community on Industrial Agents has its roots. By trying to address the system control and configuration challenges, it has expanded its application in diverse industries such as white goods manufacturing, steel, chemical, automotive, and aerospace [9]. Unfortunately, in most cases, the systematic usage of such agent-based systems never really took-off commercially, i.e., being used at large scale in industrial production environments.

Figure 1. Keywords associated with Industrial Agent publications [10]

The concept of Agent is borrowed from the domain of Artificial Intelligence (AI), where it denotes an intelligent autonomous software program. Over the years, different agent definitions, agent types, technologies, platforms, and programming languages have been developed [15]. An agent *"is capable of independent action on behalf of its user or owner (figuring out what needs to be done to satisfy design objectives, rather than constantly being told)"* [2]. Other authors have pursued, especially in the last few years, a more CPS-oriented definition: *"an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators"* [16].

Typically, modern industrial application systems require agility, scalability, robustness, autonomic features, (semi-)autonomy, collaborative behavior, efficient communication, real-time capability, semantics/intelligence, and extensibility/openness [17]–[19]. Overall, an intelligent autonomous entity that is capable of controlling a technical system, as shown in Figure 2, is a powerful design and control concept. Of interest here are some of the more "advanced" properties attributed to Industrial Agents, particularly [15]: autonomy, cooperation, responsiveness, proactiveness, smart behavior, social ability, and learning capabilities, which naturally fit the requirements of modern industrial applications. In the industrial domain, such an entity addresses many highly-pressing needs such as quick reconfiguration and system setup, cost-effective scalability, pervasive traceability, adaptiveness in dynamic environments, and rationalized articulation between vertical and horizontal integration concerns.

Agents fulfill these needs because they are inherently modular entities. Each agent can take control of different industrial resources, aligning its cyber actuation boundaries with the ones of the physical system. This is highlighted in Figure 2, where a controlling MAS creates a cyber-physical identity control relation between individual agents and production system resources. Such identity can be augmented by twining or sharing the local agent with its counterpart/or half in large computational infrastructures capable of supporting computing-intensive activities e.g., data mining and analytics, machine learning, and generally advanced Artificial Intelligence (AI) [19]–[23]. Different resources will then interact through their controlling agents using standardized interaction protocols and semantic interfaces, as shown in Figure 2. This means that with perfect alignment between the reference system architecture, and its supporting technology, it should be possible to realize "plug-and-produce" industrial resources.

Overall, the following definition covers what an Industrial Agent is, in the context of Figure 2, and encompasses how it has been used in the past and many current research efforts: *"An Industrial Agent is an agile and robust software entity that intelligently represents and manages the functionalities and capabilities of an industrial unit. While it reveals the common features of an advanced agent, it also has some specifics. It understands and efficiently handles the interface and functionality of (low-level) industrial devices. Usually, it belongs to an agent-based industrial application system within which it acts and communicates in an efficient, intelligent, collaborative, and goal-oriented way. In principle, it is an autonomous and self-sustained unit. Nevertheless, it accepts and follows company guidelines, codes of conduct, general laws, and relevant directives from higher levels. Moreover, especially in emergency and real-time scenarios, its autonomy may be compromised in order to permit fast and efficient reactions."* [17].

Current industrial systems are designed to be modular from a mechatronics perspective, yet their control structure is generally bespoke. This means that any structural, setting-up or modifying, changes are generally accompanied by time-consuming and error-prone control reprogramming processes. The agent concept minimizes such efforts by transforming the reprogramming process into a reconfiguration process, whereby Industrial Agents are not reprogrammed, but their parameters are re-tuned when they are put into operation in a new industrial context.

Over the years, several research activities have put significant effort towards enabling agents to adjust continuously to changes in their operating environment [22]. This has played both in favor and against Industrial Agents. In the first case, many prototypes have demonstrated the ability of MAS to overcome the loss of resources by rescheduling or reallocating the remaining ones. In the second case, this design trait has been often misperceived as the agent doing unpredictable things. Adaptability in a multi-agent system requires individual agents to be able to explore collectively different solutions at the face of undesirable system changes. Promoting agent negotiation, by design, has been a typical strategy to handle complex scenarios. In a multi-agent system, the effectiveness of the collective decision making is affected by the size of the set of negotiating entities, the actual negotiation and interaction mechanisms, and the complexity of operational context. In some cases, this may lead to a complex causal matrix that would make it difficult, but not impossible, to trace back all the sub-processes resulting in a specific collective action, leading to apparent unpredictability. However, according to the authors' view, the practice has shown that this sense of unpredictability is often the result of either a bad design (because the agent interactions are overly complicated and not well understood by non-expert programmers), or a bad implementation (because the intended interactions were not efficiently utilized in the development framework supporting the agent implementation) and not really an intrinsic property of agents. Such issues have already been identified as inhibitors of overall acceptance of agents in industrial settings [7].

Agents are self-contained entities, and by design, they must keep track of all the information that is relevant to their operation, as well as to the different industrial processes they participate in. This provides a kind of out-of-the-box traceability feature. It also acts as an enabler for emerging business models that require a more dynamic interconnection between consumer changing needs, the business logic, and the production activities within different production units. Here again, the self-contained nature of Industrial Agents allows, for example, individual industrial resources to be leased with variable QoS, and relatively short lease times in a profitable way. Usage may be billed in many different ways: time, functions used in the process, the context of an application, expected resource wear, the value in the overall process, etc. It is, however, always tracked cumulatively by the agent, which constitutes the base for estimating the equipment's condition and its remaining value.

This is the theory, as in practice, the implementation of Industrial Agents is conceptually and technically a complex undertaking. Early initial Industrial Agent applications envisioned the agent software as a full replacement of the existing system software. However, the practice has shown over and over again, that this is a false expectation and an improper application of agent concepts. Even if the new adding-value characteristics could be in theory realized by an agent, unfortunately, the technologies used, especially in the very early applications, could not sufficiently deliver the needed control guarantees. Recognizing this, researchers and practitioners soon moved to a form of a layered control, whereby the agent was in charge of the so-called high-level-control functions, typically operating in a soft-real time fashion

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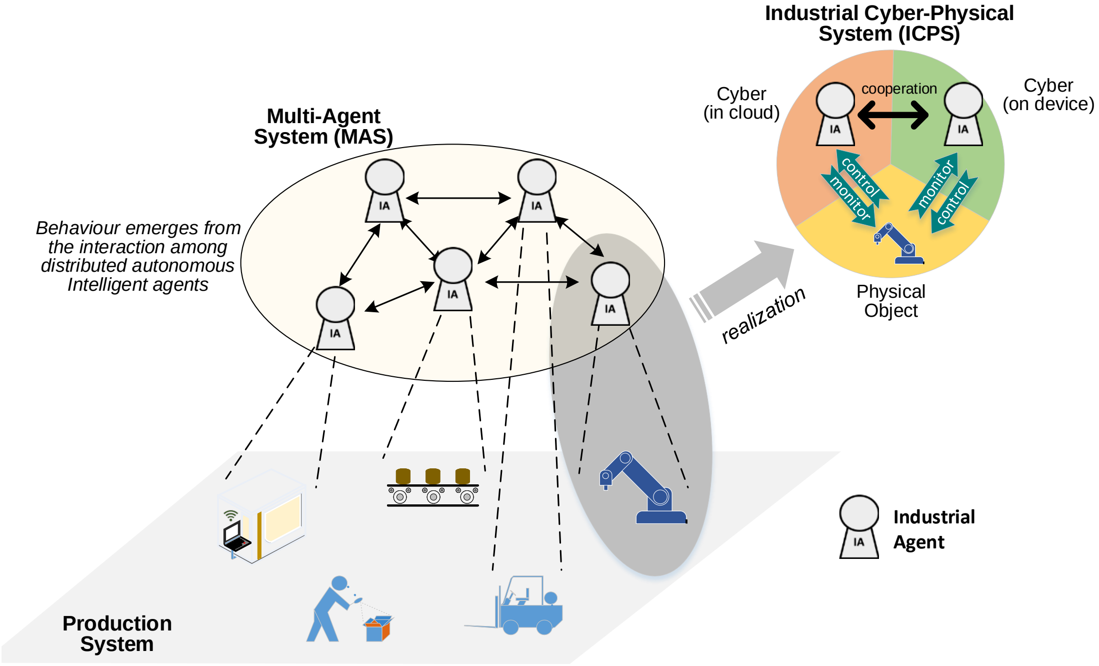

Figure 2. Industrial Agents and Cyber-Physical Systems

and native controllers that interpret the high-level-control and offer hard-real-time execution guarantees [17,24]–[26].

Currently, emerging horizontal and vertical integration concerns require most likely yet a redefinition of the concept of Industrial Agent beyond just solving control problems. Emerging approaches pursued, such as Industrial Cyber-Physical System (ICPS) and Digital Twin (DT), already capture this broader scope of action [12,13]. Does this mean that the good-old agents are dead? We seek to disprove this conjecture and demonstrate that agents have both from conceptual and technological points of view, very similar, if not the same advantages and characteristics, that are often attributed to ICPS and DTs, and therefore provide a very solid foundation for some aspects of their implementation. As such, these trends and new developments should be seen as a new chance for software agents in industrial settings to achieve the much-awaited breakthrough, as they pose a good fit for the needs of ICPS and DT.

II. INDUSTRIAL AGENTS – PROMISE AND REALITY

To create a frame of reference to assess the potential of Industrial Agents as a concept, and their effective and practical realization, one needs a set of suitable criteria. There are many possible starting points for defining or adopting such criteria. The ISO/IEC 25010 is a promising one since it establishes a set of general software quality measurements, which were found to apply well to the CPS-oriented Industrial Agents [27]. While a detailed description of these measurements can be found in [28], their general definition is provided below for reference and for clarifying the subsequent discussion. The standard [28] defines the following eight quality measurements, which the authors interpret, and comment on, in the context of Industrial Agents. The discussion addresses, for each measurement, three fundamental points: the theoretical advantages of agents, their impact and possibilities in practice today, and finally, the alternative conventional (traditional) practice.

Functional suitability refers to the degree *"to which a product or system provides functions that meet stated and implied needs when used under specified conditions"*. Proper agent design must ensure the adequacy of the solution is at par with conventional approaches. In practice, however, except for a very reduced number of effectively applied Industrial Agents, the quality and maturity of most implementations are at a prototype level. The previous must be stacked against conventional systems in operation, which, by definition, need to fulfill their design requirements.

Performance efficiency refers to *"the performance relative to the amount of resources used under stated conditions"*. Agents perform better under dynamic conditions where their inherent adaptability and self-organizing capabilities enable them to manage the system more efficiently. The practice appears to confirm that agents will indeed outperform conventional solutions in systems where change happens regularly, but also that this comes with a performance penalty, resulting from the activation of self-organizing interlocks, without a constant need for them when the system is operating in a steady-state. Conventional industrial solutions have historically been generally bespoke and fully optimized for very specific steady-state operating conditions. As such, there is a threshold, up to which conventional solutions outperform agent-based systems, and only when handling dynamic situations gains importance, agent solutions may be better suited for the same task.

Compatibility refers to *"a product, system or component can exchange information with other products, systems or* *components, and/or perform its required functions while sharing the same hardware or software environment"*. Agents will generally excel over existing solutions on compatibility, as they pose an additional layer that glues systems and functionalities. By design, they rely on structured interaction protocols that support dynamic changes with respect to reconfiguration and deployment, both of the physical system but also of the software solution. The selection of adequate technology is essential, since different technological solutions may make it slightly easier or more complex to attain compatibility. Conventional solutions are generally only compatible within a given product range, however, with the interplay of IT and OT over the last years, approaches that can handle such complexities (like industrial agents) gain importance.

Usability refers to the degree *"to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use"*. The superior expressiveness of the languages and platforms supporting agent-based solutions should enable the design of Industrial Agents that can handle or support rather complex decision making processes. In practice, most of the advanced decision-making processes need to be tailored to particular operational scenarios and are not available out of the box neither from the agents, as a concept, nor from their supporting technologies. Usability in conventional solutions is always tailored to use-case specifications. The high customizability at the agent layer and the interactions they support could also lead to approaches that are more tailored to the needs of specific users at that last mile e.g., the end-user interface. This can be done at agent-level, without affecting any aspects of the technology stack below. Increasing usability of conventional solutions could be realized by new approaches, that are built on top of the agent layer. However, the complexity of making conventional solutions more usable, may be comparable to the effort of introducing a new agent-based solution overall.

Reliability refers to the degree *"to which a system, product or component performs specified functions under specified conditions for a specified period of time"*. The reliability of the agent-based systems is by design high as they are usually distributed and have fallback strategies. Agents feature a modular and decoupled design that relies on well-defined agent interaction protocols, that ensure that from a logical point of view, a failure within an Industrial Agent will not directly affect other agents. In case of failures or unreliable communication systems [29], the agents can implement effective fault-tolerant interactions. In addition, failing or misbehaving agents may be stopped, cloned, respawn, and as such, they support many modern-system functionalities that are similar to state of the art also at other levels e.g., container-based technologies. Agents are still affected collectively by failures in their supporting computational infrastructure and software bugs, but unless these hit all the agents at the same time, by chance or a coordinated attack, the agent-based solutions shall denote a high level of Cyber-Physical reliability. This has been demonstrated in practice and is a hallmark of agent-based design. Nowadays, infrastructure services get their own dynamic lifecycle management characteristics e.g., running in containers, where modern technologies such as Kubernetes can maintain a level of QoS over the whole infrastructure, which addresses such reliability and availability issues. Therefore, by coupling agents with an increasingly reliable infrastructure, the overall reliability of the system increases. On the opposite side, conventional solutions denote a much more coupled logic design that facilitates the propagation of failures and usually requires the usage of redundant resources in critical systems.

Security refers *"to which a product or system protects information and data so that persons or other products or systems have the degree of data access appropriate to their types and levels of authorization"*. Agent security highly depends on the supporting platforms/services, and implementation patterns followed. However, by design, the decoupled design creates additional opportunities for attacking the agent itself, the agent platform, or the systems they interact with. Although significant work has been invested in making all these e.g., agents, platforms, and interactions secure, over the years, these are still at a high-level depending on specific platforms, and there is a lack of an overall security best practice. Such action can be attributed to the still isolated industrial systems where agents were operating, but is not up to date with modern highly interconnected ICPS. As such, more sophisticated approaches, including verification of agent security at agent, agent-system and overall solution level has been left relatively unattended over the last years by the research community investigating Industrial Agents. Despite this, agents can also act as enablers of trust and security, as they can mediate among the different stakeholders and resources to be accessed.

Maintainability refers to the degree *"of effectiveness and efficiency with which a product or system can be modified to improve it, correct it or adapt it to changes in the environment, and in requirements"*. The modular nature of agents should make them inherently easier to maintain, as adjustments can be carried out only in specific agents, and functionalities can be incrementally introduced. However, this advantage stands from a Cyber-Physical holistic perspective. Generally, the existing software supporting agents e.g., agent platforms, suffers from the same maintainability challenges itself as any other software solution. Version changes can be particularly problematic, depending on the selected platform, and the maturity of the platforms and the software developed on top of them is also usually a problem. Practically, plug-ability and flexibility have been demonstrated in several Industrial Agent prototypes, but these are mainly Cyber-Physical advantages. Guaranteeing, for example, the success of these operations after a software update is something that has not received sufficient focus in the Industrial Agents domain.

Portability refers to the degree of *"effectiveness and efficiency with which a system, product or component can be transferred from one hardware, software or other operational or usage environment to another"*. Agents are generally quite portable by design and usage of their supporting technologies. Such capability has been demonstrated in practice and is one of the big advantages of agents. In conventional systems, portability is usually problematic, and its success depends very much on the quality of the supporting software. Depending on the nature and functions of the software, it may or may not

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be well-supported.

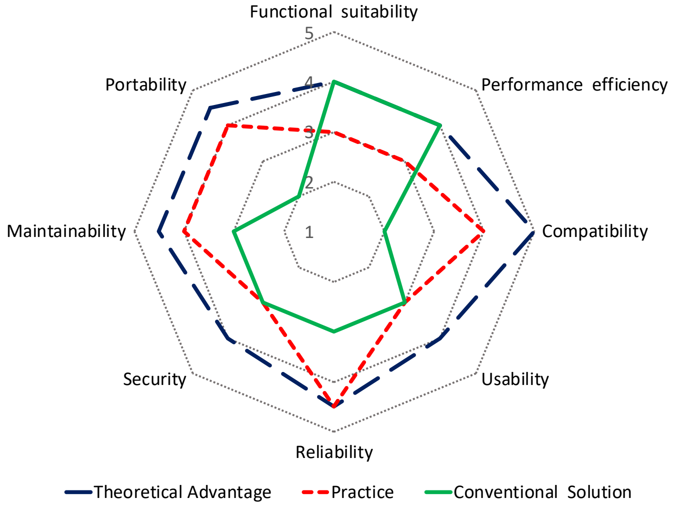

Figure 3. Comparison of agent-based theory, practice and conventional approaches

What has been evident after over two decades of development and demonstration of Industrial Agents, is the existence of a gap between what the theoretical advantage promises, what the practice shows and what conventional solutions have realized so far. According to the authors' experiences, these gaps can be easily communicated in Figure 3 that also summarizes the discussion so far. Figure 3 makes it clear that even if in most measurements the agents would provide an almost immediate advantage over the next best solution, in practice and when stacked against the next best conventional practice, there are still important gaps, that overall slow down the acceptance of Industrial Agents as a design concept and of their supporting technologies. Such findings are also in line with the findings in the domain of software agents overall [7]–[9,19,30]–[34].

III. PAST AND PRESENT EFFORTS

The usage of agent technology is being researched in prototypes and niche industrial solutions in a variety of domains, including manufacturing, logistics, smart grids and telecommunications. Industrial agent solutions take advantage of agent-inherent characteristics to develop complex large-scale Systems of Systems (SoS) [35] that exhibit modularity, adaptation, reconfiguration, and responsiveness to the conditions change. Several surveys are available in the literature reporting the industrial applications of agent technology, as well as innovation projects carried out in the last years [9,30,32,36].

An analysis of surveys shows that, in terms of industrial environments, initially, the Industrial Agents were applied in the manufacturing field due to its inherent characteristics to address modularization, robustness, and reconfiguration. Progressively, the areas of interest addressed by Industrial Agents were growing, also becoming applied to other fields, namely smart grids and logistics. According to an analysis [10] of the IEEE IES Industrial Agents Technical Committee publications [11], manufacturing and control occur very frequently in the published paper titles on the early stage, i.e., before 2011, but still predominant after 2011. However, after 2011, other interest areas start appearing in the literature, e.g., energy, power, self-*, scheduling, and grid. This means that Industrial Agent applications in the energy domain have gained important traction in the last few years, largely following the global trend of amalgamating software approaches with key power grid elements and applications.

The earliest and most well-known application of agent technology in an industrial environment was conducted in a production line for producing cylinder heads for four-cylinder diesel engines at the Mercedes-Benz (now Daimler) factory plant in Stuttgart, Germany [37], known as Production 2000+ (or simply P2000+) system. The agent-based solution aimed to introduce reconfiguration and adaptation in the assembly line and was in operation for five years up to the end of the life-cycle of the targeted product, being reported an increase of productivity of 20% [37]. At the time, the application of agent technology, focused mainly the manufacturing control and planning and scheduling application domains, with several applications of Industrial Agents also conducted to, e.g., increase the machine utilization at the steel rod bar mill of the BHP Billiton in Melbourne, Australia [26], and support the scheduling in the engine assembling workshop of SKODA Auto, Mlada Boleslav [38]. In some solutions, MAS is enhanced with holonic principles [5,21,26,39,40], taking advantage, amongst others, of the recursive capability that simplifies the design of such systems. An example of such holonic MAS system is the manufacturing execution system (MES) developed for the American Glass Product (AGP) company that produces laminated security glass for automotive applications [40]. These comprise only some examples of industrial agent applicability, while several other projects have also demonstrated the concepts and technology widely [9].

In the domain of the smart grid, MAS are used to address some automation functionalities, e.g., the demand side management, distributed control and monitoring, self-optimization, and energy markets. For instance, MAS have been used in some innovation projects to implement a real-time energy market driven by producers and consumers of distributed energy resources that have been implemented with agents that do the trading [41]–[43] and optimize local resources, e.g., in buildings [44]. Agent-based systems, such as the Powermatcher [45], have also been used for coordinating load management among different energy stakeholders. Such efforts have also led to intelligent control of microgrid loads via agents to maintain the balance between the energy demand and supply through a selective shedding of low priority loads [46]. There have also been successful efforts where different agent-based approaches have been mixed with other non-agent systems and have led to the effective management of grid load at neighborhood levels [47].

In logistics, several applications were reported related to scheduling and optimization, namely those related to taxi real-time scheduling for the corporate Addison Lee taxi company, the real-time transport optimization for the European logistics company ABX Logistics [48], the rent a car optimization for

Avis, U.K. [49] and the real-time scheduling for the LEGO Company supply chain [50].

In terms of application scope, a deeper observation on the reported Industrial Agent based applications shows that, in the past, Industrial Agents were more focused in control and automation, planning and scheduling, and monitoring, diagnosis, and management. In recent developments, these application areas still hold their relevance and constitute the core, while other application areas are growing significantly, such as engineering, integration, and simulation. The increasing relevance of engineering and integration is easy to follow, as there is a growing need to move beyond basic monitoring and control aspects, towards engineering sophisticated ICPS, and ICPS-based ecosystems, where the integration of cyber and physical counterparts assumes crucial importance.

In terms of simulation, NetLogo [34] is a good example of an agent-based modeling and simulation platform, and AnyLogic is an agent-based simulation system, which is being used to model and simulate complex and large-scale systems. Several applications in the simulation area are reported, e.g., to analyze the impact of disruptions on the shop-floor production for an automobile parts facility for a real-life large-scale OEM [51], and the analysis of the risks of maintenance activities within a Liquefied Petroleum Gas supply chain using the AnyLogic simulation software platform [52]. Modeling and simulation also expand towards ICPS [8,18,53] as well as other more strictly regulated domains such as eHealth [54].

IV. ACCEPTANCE OF INDUSTRIAL AGENT APPROACHES

Industrial Agents comprise of key concepts and technologies that act as enablers of larger complex systems. In industry, the end-product, independently of the technologies used, needs to be accepted, which constitutes an excellent match at different dimensions, including technology, production use, costs, etc. While Industrial Agents hold a good potential for diverse utilization in industrial use cases [1], their wide industrial acceptance has been very limited and still remains a goal yet to be achieved. After almost two decades from the introduction of Industrial Agents in production environments, namely the P2000+ system [37] at Mercedes-Benz (now Daimler) in Germany, agent-based approaches have not been widely adopted in industrial production environments. Even in the recent past, while several research and innovation projects demonstrated specific use-cases and prototypes utilizing agent technology and concepts in industrial environments, we are yet to see them leaving the (usually short term) prototype level and progress towards long-term deployments.

The reasons behind the lack of success of Industrial Agents, should not be sought on mere technological terms or a limited number of benefits, e.g., in flexibility. One of the key lessons learned is that success in the industry has to make evident the business benefits in real-world cases and their requirements. However, most of the efforts so far have mostly attempted to prove the concepts of agents at large, in the best possible technology-driven way, without paying sufficient attention to other factors. To make this point evident, consider the P2000+ system, which, despite the evidenced robustness and higher productivity, was not further pursued, as its technical advantage did not imply an immediate and measurable economic advantage [37]. Often technical factors are given asymmetrically more focus rather than the business counterparts. Hence technical excellence is sometimes pursued to the extremes when, in reality, a more technically-limited approach could suffice for the specific industrial case, and strike a better balance between cost and benefits. For instance, the P2000+ system could process any kind of product (high degree of flexibility); however, in practice, only 2–3 variants would be adequate (limited flexibility) for the business purposes [37]. As a result, other substitute technologies, although overall less flexible than the agents, but still within the limit of providing the limited flexibility needed in the P2000+ cases, ended up being used due to their lower cost and complexity.

Another example comes from the telecommunication sector. Telecom Italia, which is a large telecommunications provider in Europe, realized WANTS [55], an agent-based platform running hierarchical workflows for the management of broadband telecommunication networks and services. WANTS had a direct impact on *”thousands of technicians and on millions of customers”* and overall was *”regarded as a best in class system”* [55], that enabled high performance, scalability, robustness, control, maintainability and fault tolerance, as well as extensibility in defining and modifying services. Despite this development and operational success, some barriers hindered the widespread acceptance of the agent-based platform. Key factors included insufficient support tools and methodologies, as well as the utilization of agent-specific terminology, e.g., proactivity & self-consciousness, which seems to be clashing with the traditional mindsets in the industry that require total control, especially of mission-critical systems [55]. In this industrial case also, it seems that satellite factors and not the technology itself seemed to hinder its acceptance at large scale.

A recent survey [1] has attempted to identify these additional key factors from a multi-angled view (covering technology, business, etc.), that can be linked to the acceptance of the agents in industrial environments [7]. As shown in Figure 4, it was hypothesized that the key factors that could be significant are: Design, Technology, Intelligence/Algorithms, Standardization, Hardware, Challenges, Application, and Cost. Rigorous statistical analysis on the acquired survey data indicated that indeed, all of these were relevant and contributed to the acceptance of agents in industrial settings [7]. This empirical affirmation had been for some parts already hypothesized, but mostly for the technical side, while in a qualitative manner other reasons were also pointed out [30,31,56] e.g., the investment to set up agent-based solutions, the compliance to standards in order to fulfill industrial requirements, the lack of agent programming skills, etc. The quantitative empirical approach significantly expanded the inclusion of other business-relevant decision factors [1,7], eventually making clearer the spectrum of issues Industrial Agents need to address to achieve their breakthrough and acceptance for production use in industrial environments.

Today, most of the experiments are carried out, still in limited trials within various research and innovation projects [9], as a result of the cooperation of academia and industry.

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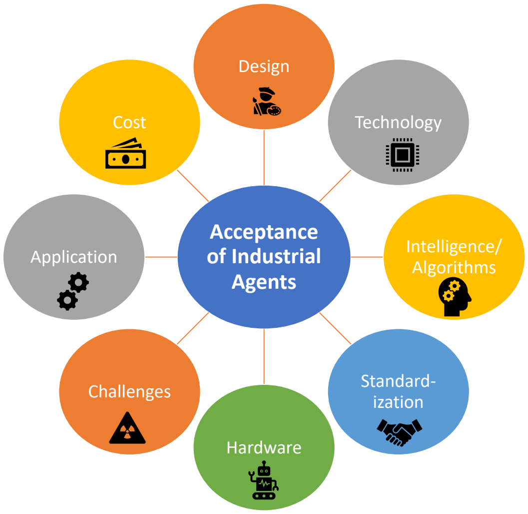

Figure 4. Industrial Agent Acceptance Factors [1,7]

Efforts seem to be more scenario-driven and gear towards demonstrating the benefits in specific scenarios. However, such efforts have not yet managed to make the jump from prototypes in industrial environments to large scale production use. While technical features may lead to success and demonstrate technical excellence, they won't be sufficient if they are not accompanied with equally good performance at other dimensions, e.g., cost. The additional benefits need to be tangible, understandable, and not solely in the mid or long term, as business decisions need to be made increasingly consider short-term due to the rapid pace by which modern information and communication technologies progress.

It has to be pointed out though, that industrial infrastructures are becoming increasingly complex, and agent concepts and related technologies are only a part of a broader ecosystem. Industrial Agents always have in the past competed with alternative state of the art technologies and solutions e.g., for integration [6,9,30,57], and will continue to do so with any market solution that offers similar benefits, that may even be technologically inferior, but at a better price tag. Strong coupling with the business side is needed, in order to find an equilibrium of technical excellence, cost-effectiveness, and business utilization [7], that could enable the breakthrough of agents in industrial environments as a technology of choice. Hence Industrial Agent solutions need to position themselves as a good fit to industrial landscapes, compete with similar approaches on all fronts (economic, business benefits, technology) that the specific industrial case requirements mandate, and prove that overall they pose a better value for any business to invest in, rather than other alternatives. We need to reinforce that any such efforts need to be based on realistic industry requirements for the specific envisioned use-cases and offer tangible business benefits for the envisioned use-case.

V. STANDARDIZATION AND BEST PRACTICES

A. *Agent Standards*

Standardization plays a pivotal role in the adoption of any technology, and this also includes the Industrial Agents as the various surveys attest [7,8,30,31,36]. However, such standards should not be one-sided, e.g., coming solely from the Industrial Agents community, but be well-placed among other industrial standards, consider the latest advances in Internet and web technologies, and preferably be open as the survey [7] attests. While some standards exist in the agent domain, these are outdated, and not well-integrated with the existing ones, e.g., in industrial automation, nor the standards being underway in Industrie 4.0.

The primary standards for the development of agent-based applications were created by the Foundation for Intelligent Physical Agents (FIPA) [58]. FIPA was originally established in 1996 to produce software standard specifications for heterogeneous agent-based software engineering. In 2005, FIPA was officially accepted as a standard by the IEEE Computer Society standards organization that promotes agent-based technology and the interoperability of its standards with other technologies. FIPA defines a set of specifications for the development of agent-based solutions, namely defining the application areas where agents can be deployed, the abstract entities that are required to build agent services and an agent environment, and the way the agents communicate by Agent Communication Language (ACL) messages, interaction protocols, speech act theory-based communicative acts and content language representations. FIPA also specifies an agent management model that comprises several components, namely the Agent, Directory Facilitator (DF), Agent Management System (AMS), Message Transport Service (MTS), Agent Platform (AP) [59]. The Java Agent DEvelopment Framework (JADE) [33] is the most popular framework to develop agent-based systems that is FIPA compliant.

Another standard stems from the Object Management Group (OMG), which created the Mobile Agent Systems Interoperability Facility (MASIF) standard [60]. MASIF addressed several aspects of the mobility of agents, including agent control, migration, and locating of agents. The MASIF standard focused on the interfaces among the agent systems, rather than between agent applications and agent systems, to explicitly tackle interoperability among the agent systems.

While FIPA found widespread utilization in agent platforms, MASIF adoption had been limited. Nowadays, both MASIF and FIPA are seen as outdated and do not cover the developments in ICPS domain or the broader I4.0 technologies and architectures. Industrial applications impose specific and strong requirements, namely integration with hardware devices, industrial standard compliance, reliability, fault-tolerance, scalability, quality assurance, resilience, manageability, and maintainability, that may affect the adequacy of the FIPA specifications, and consequently its adoption in industry [7]. However, FIPA and MASIF insufficiently address the development of Industrial Agents, as they do not cover the integration of physical devices, as also existing common practices reveal [22]. In addition, both FIPA and MASIF do not address the need for real-time interaction protocols for industrial and large-scale systems, ensuring scalability and high performance, while combining them with complementary paradigms/technologies to overcome some agents limitations, e.g., with SOA (Service-oriented Architectures) to achieve interoperability and IEC 61131/IEC 61499 in order to fulfill real-time constraints.

In the era of ICPS, there is an evident need to address Industrial Agent integration & communication patterns, especially with physical hardware device integration that performs (real-time) control, e.g., a smart meter, PLC (Programmable Logic Controller), robots [61]. As an example, such area has been the focus of the IEEE P2660.1 working group [62], where common practices [22] pertaining to the integration of software agents with the low-level real-time control systems is investigated, assessed and guidelines and design patterns are provided. However, it is clear that new standards are needed that effectively embed Industrial Agents in the ICPS domain. Existing standards such as FIPA, in order to remain relevant, need to be updated to adhere to contemporary and promising Industrial Agent active areas of development, as also indicated in Table I.

B. *Best Practices for Industrial Agents*

Beyond standards, a key complementary activity is how to create best practices for the utilization of Industrial Agents. This is not a new need, but as already discussed, and also revealed in the empirical survey [7], there is a lack of sufficient tools and methodologies on how to successfully utilize Industrial Agent concepts and technologies. The result is often that a dangerous mix of inexperience, bundled with false expectations, and utilization in inappropriate scenarios, may lead to distrust in the technology itself and its potential industrial applicability. As such, what is needed are best practices for specific domains and scenarios that have in practice proven themselves to be a good fit. In addition, guidelines on how to best implement such practices or adjust practices from other domains or scenarios to the user-specific use-case are needed.

While the need is there, today, after several years of prototypes and implementations of software agents in the industry, we are still at the initial stages, where a best-effort and learning-by-error are still the main ways that developers learn and utilize the technologies and concepts. The ongoing work in IEEE P2660.1 working group [62], beyond its technical investigations, also has as a goal to provide an approach where Industrial Agent practices can be assessed by specific criteria, and be scored. Such a scoring would enable the comparison among existing practices and also provide an indication of its strong and weak points.

A starting point for such criteria is to use the product quality model characteristics defined for software systems in ISO/IEC 25010, most of which seem relevant and essential for Industrial Agent solutions [27], and bring out the key benefits as outlined in section II. However, an analysis at the concrete measures as these are specified in ISO/IEC 25023 has revealed that the suitability of these criteria for Industrial Agents varies significantly [63]. It is important to note that ISO/IEC 25010 also defines in-use criteria that capture the feedback once the system is operational. Specifically, effectiveness, efficiency, satisfaction, risk, and context coverage are captured. Therefore, here a need emerges to fine-tune or create new metrics that properly capture the characteristics of Industrial Agents to their full extent (both during development and during production utilization), in order to also enable comparison of common practices as well as available solutions.

Assuming though that such criteria are available and concisely defined, the next step is to collect existing practices, score them against the criteria. Such a system is needed to enable the submission, storage, and analysis of practices and their scoring with the goal of capturing the community knowledge from industrial implementations of agent-based concepts and technologies. Driven by the available data, then recommendations can be realized when a user searches for the best practice that is a good match to his/her requirements. In that sense, successful realizations of agents will propagate, while in parallel, inexperienced developers or solutions providers would be provided with guidelines and decision support in order to increase the chances of properly utilizing agents for their specific use-cases and achieve their goals. Such work is seen as critical to be investigated in detail in the future, as it can strike a balance between theoretical frameworks, their available realizations, and industrial needs and experiences.

VI. THE WAY AHEAD

A. *A Contemporary Definition of Industrial Agents*

The definition and targeted scope of the Industrial Agent community have been adapting to different domains and needs over the years, as it has already been discussed. With the emergence of Cyber-Physical Systems, and the strong correlation with Industrial Agent research [9,19], an adjusted definition that better reflects the scope of Industrial Agent research for the recent and upcoming years is needed. The aim is to have a clear positioning of Industrial Agents in the contemporary context of concepts and technologies, that would also enable a low learning curve for newcomers in the area as well as remove potential ambiguity.

An Industrial Agent is an autonomous and self-contained Cyber-Physical entity that intelligently represents and manages the functionality of one or more industrial assets that are, permanently or temporarily, physically coupled with the purpose of executing the functions and processes made available by the Industrial Agent. The cyber part of an Industrial Agent integrates various software solutions that collectively address the representational, management, control, and execution concerns of the physical part, in an ideally standardized way. The physical part of the Industrial Agent includes all the physical components and computational platforms required for the Industrial Agent to carry out the function(s) it was designed for. This approach recalls the holonic principles, where a holon comprises an information processing part and a physical processing part when it represents a physical device.

Industrial Agents are expected to operate and be part of a much larger Cyber-Physical ecosystem that also includes other Industrial Agents and decision-making systems and services, all of which dynamically interact or collaborate, not only influencing each-other but also giving rise to self-organizing behaviors. These additional services provide a framework for articulating horizontal and vertical integration concerns at ICPS level (including ICPS constellations).

Preprint version of doi:10.1109/MIE.2019.2962225

Such a definition and context, as analyzed above, fits well with modern pursuits in the ICPS and Industrie 4.0 context. As an example, the Asset Administration Shell (AAS) defined as part of the RAMI 4.0 [64] can be realized with agent concepts and technologies. The AAS [65] offers an interoperable way to capture key information pertaining to assets such as asset properties, physical and virtual characteristics, conditions, operational parameters, sensed/calculated measurements, intrinsic capabilities, etc. and enable the easy interaction over standardized, secure communication with other I4.0 components. Agents could be used to either implement the AAS itself or support some of its key functionalities [19], for instance, data gathering, physical object encapsulation, communication, collaboration, negotiation, re-configuration, and intelligent decision-support. As such, via the AAS, any asset (e.g., an Industrial Agent based ICPS) is becoming part of the value chain and can utilize as well as generate added value.

Considering the industrial needs and emerging directions of industrial research, it is necessary to grasp the overall positioning of Industrial Agents within the broader scope of ICPS. As shown in Figure 5, which is extended from [66], for the ICPS there are three important dimensions in this equation, namely:

- physical – reflecting the physical boundaries of different modular industrial resources;
- logical – reflecting the new infrastructures (covering computational, communication, storage, and service aspects) that are available for the deployment for the industrial Cyber-Physical resources;
- cyber – reflecting interoperable intelligent interactions (e.g., via smart adaptive response algorithms) between all the components and services within the system as well as in the broader ecosystem.

The next generation of ICPS is expected to operate in a broader ecosystem that is rich in services, reactive but also pro-active interactions, and communication among its smart stakeholders. Such ICPS ecosystem is reflected on the left side of Figure 5, where the ICPS adheres to the I4.0 standards and becomes an I4.0 component that can contribute to as well as benefit from the ecosystem. Figure 5 makes it clear that the AAS plays a pivotal role in transforming the ICPS to an I4.0 component and thereby enabling its interaction to the available I4.0 ecosystems.

In the context of Figure 5, it can be seen that the scope of agents is greatly enlarged with respect to past efforts, as it encompasses not only control but also resource representation, intelligent decision making at resource and system level, and forms the basis for more intelligent systems and emerging behaviors at the system of systems level. All these new and refined aspects are not sufficiently considered in the traditional scope of an agent as a single piece of executable software, sometimes associated with physical objects (physical agents, holons, etc.), as it has been traditionally considered. As such, the scope of the Industrial Agent is extended and becomes:

- on the ICPS side – the collection of software and hardware (incl. platforms, tools, algorithms, etc.) that are perfectly integrated to create a consistent Cyber-Physical unit;
- on the ICPS ecosystem side – agents will play different roles in information collection, processing, and of making use of that information to coordinate, in an intelligent fashion, the system's behavior.

B. Promising Research and Development Directions

Industrial Agents and their supporting technologies will definitely play a role in the future, especially considering key enabling technologies in the ICPS context. Key challenges for ICPS have been explicitly laid out [12,13,67] covering the main areas of development. Such challenges are not only at ICPS system level but also at System of Systems level (SoICPS) [18,35], and include management, engineering, capabilities, infrastructures, ecosystems, and information systems. Industrial Agents have the potential to make significant contributions to several challenges already identified for ICPS [12], as shown in Table I which is extended from [12,13,67].

We have argued that Industrial Agents and ICPS are intertwined in the scope of I4.0 and because Industrial Agents possess several characteristics, as discussed in section II, in relation to ISO/IEC 25010, this enables them to contribute to the manifold ICPS challenges. Such contributions are in-line with already pursued and planned research activities within the agent community, especially when ICPS is considered in the different domains. As an example, with respect to Cyber-Physical Production Systems (CPPS), explicitly design patterns, metrics, interfaces, and distributed intelligence are investigated [19].

In terms of *ICPS Capabilities*, Industrial Agents can be beneficial to support the development of modular ICPS, some of which may also be a formation of different devices and services "glued" together. Traditional aspects of monitoring, diagnosis, and control could be utilized to support reactive ICPS that collect data, analyze them, and adjust their behavior accordingly. Agents have widely been used in planning and optimization tasks, and their capabilities could be assisting in data-driven decision making, as well as proactive behaviors of the ICPS. The use of agent technology allows the distribution of intelligence by different computational layers [57], ranging from cloud to fog and edge. In a similar manner, due to the autonomous interactions within a MAS, autonomic, and self-* ICPS, that exhibit emergent and collaborative behavior may be realized.

In terms of *ICPS Management*, lifecycle aspects of ICPS may be delegated to Industrial Agents, which can address complexity and interaction issues. Agents have intrinsic characteristics that enable them to negotiate [68] and interact in uncertain environments, which could help, especially with the coordination among different systems that are governed by various stakeholders. Security, safety, and trust aspects could also be considered, e.g., agents could be roaming an ICPS ecosystem and do vulnerability analysis as well as patch opportunistically connected systems and IoT devices. Coupled with the reasoning and intelligence capabilities of agents, key challenges in the lifecycle management of ICPS as well as larger SoICPS could be addressed.

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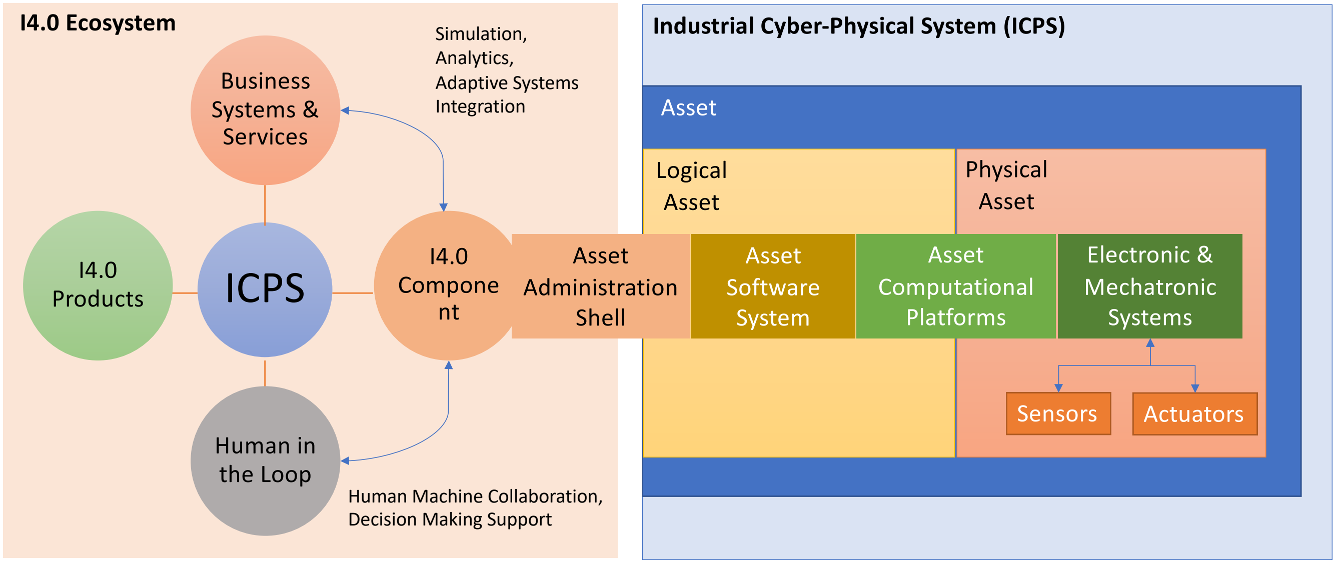

Figure 5. The ICPS and the I4.0 ecosystem

In terms of *ICPS Engineering*, Industrial Agents can provide help by realizing tools for the design, simulation, integration, assessment, and implementation of complex large-scale systems exhibiting modular and self-* behaviors. Especially ICPS challenges, such as resilience, graceful degradation, validation, and testing, could be addressed by Industrial Agents, that proactively identify risks and take risk-mitigation actions. New programming languages and middlewares are expected to emerge within ICPS community, and MAS platforms could pose as such a middleware. However, existing popular MAS platforms (e.g., JADE [33]) will need to be extended as they already face several problems that may inhibit their applicability, e.g., lack of hard-real time execution, limited scalability, and centralization of some internal services.

In terms of *ICPS Infrastructures*, connectivity with other systems and services is crucial, and to realize it, interoperability comes forward as a natural ingredient and research direction. Agents can play a role by mediating among systems and services, while also enabling the integration of legacy systems/services and supporting the migration processes. The interface between the agent, as a cyber-part, and the physical asset constitutes the first step in the digitalization process of existing systems, as advocated by the layered RAMI 4.0 reference architecture [64]. Therefore, it is of pivotal importance to establish a proper, open, scalable, reusable and responsive interface between the software agents and the asset placed at the different levels of the ISA 95 model, namely sensors and actuators at the field level, robot controllers or PLCs (Programmable Logic Controller) at the control level, SCADA at the supervision level, and MES and ERP (Enterprise Resource Planning) at the factory level, but also with products and humans. As such, agents could provide the backbone for integration, resilience, robustness, and sustainability, especially in industrial and critical infrastructures and their associated services.

In terms of *ICPS Ecosystems*, agents can once again provide added value due to their self-* capabilities, and in conjunction with modern AI approaches, enable ICPS to learn [23] and autonomously operate in highly-dynamic environments either as standalone entities or as part of larger ecosystems. Agents could act as enablers of the collaboration capabilities and enable sophisticated interactions among ICPS, who could commonly address larger goals within the I4.0 ecosystem [18]. Training in the envisioned I4.0 environment where a seamless collaboration of humans and machines is envisioned is an issue, and agent-based systems are investigated in such environments [69]. In addition, agents are a good fit for dialog management tasks, e.g., digital assistants and automated chat interfaces [70]. As such, Industrial Agents may be utilized to realize the vision for ”human in the loop” in I4.0, where the shop-floor personnel interacts with the help of agents with its surroundings and ICPS. This might ease the workforce ramp-up with new ICPS technologies and eventually enhance their performance and satisfaction in the I4.0 context. In addition, it seems that the creation of knowledge and identification and adoption of metrics and best practices, as discussed in subsection V-B, are common for both agents and ICPS, so addressing it at the agent level, could act as an enabler for ICPS and benefit them at least from the process and methodology viewpoints.

In terms of *ICPS Information Systems*, the agents can already benefit ICPS due to their capabilities in collecting and analyzing data, processing information, and extracting actionable knowledge, as well as utilizing intelligent approaches, reasoning and negotiation [19,22,68]. Such skills for data management and processing are integral in the I4.0 context [71]. The agents, as information and knowledge consumption/generation entities, have the potential to empower ICPS with these features and enhance their operations. Such actions can be carried out not only at ICPS level but also at SoICP,

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Table I
KEY ICPS CHALLENGES AND SUITABILITY OF INDUSTRIAL AGENTS

Area	Key Challenges	Difficulty	Priority	Industrial Agent Suitability
ICPS Capabilities	Real-time monitoring, control & management of ICPS / SoICPS	high	high	Fair
	Seamless (real-time) service-based interaction of ICPS with human-actors/users	high	high	Very Good
	Optimization in ICPS and their task-specific application	high	medium	Good
	On-ICPS advanced analytics and decision making	medium	high	Very Good
	Sentient SoICPS: Autonomous collaboration among ICPS	high	high	Very Good
	Energy efficient ICPS	medium	medium	Good
ICPS Management	Lifecycle management of ICPS	medium	medium	Very Good
	Management/coordination of multi-domain large scale ICPS and SoICPS	high	high	Very Good
	Security and trust management for ICPS and SoICPS	high	high	Fair
ICPS Engineering	Model-based engineering methods covering the full life cycle of ICPS and SoICPS	high	high	Good
	Safe programming, validation, resilient, risk-mitigating ICPS and SoICPS	high	high	Very Good
	Engineering tools and practices for ICPS lifecycle support	high	high	Good
	New operating systems and programming languages for ICPS and SoICPS	medium	low	Weak
	Simulation of ICPS and large-scale SoICPS	medium	high	Very Good
ICPS Infrastructures	Multi-domain ICPS interoperability, management, control, QoS etc.	medium	high	Good
	Migration solutions to full ICPS infrastructure and cohabitation with legacy systems	medium	high	Very Good
	Integration, resilience, robustness and sustainability of ICPS critical infrastructures	high	high	Very Good
	Provision of ubiquitous ICPS data & information services	medium	medium	Very Good
	Economic, social, environmental etc. impact of ICPS infrastructures	high	high	Weak
ICPS Ecosystems	Autonomic and self-* featured ICPS	high	medium	Very Good
	Education/training to enable fast assimilation of ICPS (humans in the loop)	high	high	Good
	Collaborative ICPS (intelligent autonomous ICPS collaboration)	medium	medium	Very Good
	Cross-industry knowledge base, best practices & emergent behavior at SoICPS level	high	high	Very Good
ICPS Information Systems	Artificial Intelligence in ICPS / SoICPS	high	high	Very Good
	Cross-Domain large-scale information management in ICPS infrastructures	medium	low	Good
	Transformation of ICPS data and information analytics to actionable knowledge	high	high	Fair
	ICPS automated knowledge-driven decision making, management, and risk analysis	high	medium	Very Good
	Autonomous smart ICPS within an ambient-intelligent-ecosystem	high	medium	Very Good

effectively generating added value for the ICPS as well as the ecosystem it operates in.

As can be seen, there is a good match for many of the ICPS challenges and agents, where the latter could act as enablers and assist towards ICPS achieving their envisioned functions [8,19,22]. Especially areas considered as of high priority and high difficulty where Industrial Agent suitability is very good, have the potential for significant impact in the long term, that may further establish Industrial Agents in the context of ICPS, e.g., sentient SoICPS. However, areas with a lower degree of difficulty but also high priority may be more attainable in the mid-term and potential contributions there might spark new interest in the agent concepts and technology with an application to ICPS, e.g., simulation of ICPS/SoICPS.

VII. CONCLUSIONS

Diverse Industrial Agent concepts and technologies have been developed over the last two decades and realized in industrial prototypes. However, we have yet to see long-term utilization of solutions at large scale production systems in

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the industry. Such acceptance is usually a complex undertaking that relies not only on the technical excellence of a solution but also on the tangible business benefit in the short term and the fierce competition with other similar technologies, which may offer better technical excellence and cost ration. However, with the emergence of ICPS and its application in various domains (energy, manufacturing, logistics, etc.), a new chance has risen for agent-based approaches. The reasons lie within the excellent matching of ICPS challenges that need to be tackled and the intrinsic characteristics and capabilities of agents that could be utilized in order to address the ICPS challenges. Such an undertaking is not trivial, and requires an update of the Industrial Agent definition, as discussed in this work, as well as a mindset shift from the research community to focus on the ICPS as a major objective and consider the needs and operational context of the needed industrial solutions.

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