Intelligent Industrial Processes: Enabling Research Challenges by Dependable Communication and Computation

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**Preface**

Efficient industrial processes are a key enabling factor of economic and social growth in modern societies. Several initiatives on projecting the development of industrial process automation in the future were undertaken by different research groups, industrial forums and governmental organizations.

This document reflects upon the major industrial trends, socio-economical demands as well as long term visions of the future technology. The reflection focuses on scientific challenges in the areas of computation and communication systems, which need to be addressed in order to achieve the desired functionality and foresee intelligence in future industrial processes.

The document consists of two parts. Part I introduces concepts and categories to be used throughout the text and presents the results of the analysis of the international research agendas. Part II presents the research challenges based on the analysis of the state-of-the-art.

**Part I. Industrial development 2030 and beyond**

Part I of the document is structured as follows. Section 1.1 summarizes the concepts and categories to be used throughout the document. Section 2 presents the analysis of the considered research agendas.

1. **Concepts and Categories**

The main focus of the present study is future industries. The definition of the modern industry spans way beyond a single factory focusing on manufacturing of a particular product. In the context of this report by industry it is understood a set of actors along with the business, social and technological relationships between them resulting in the production of one or another final value.

The business, social and technological relationships in this context refer to the relationships across the entire value chain leading to the production of a certain value including business-level contacts, logistics, manufacturing, services, etc.

The creation of a certain value happens thus through a chain of industrial processes.

The traditional definition of an industrial process tells that the *industrial process* is a systematic series of mechanical or chemical operations that produce or manufacture something. Another definition of a similar kind tells that the *industrial processes* are procedures involving chemical or mechanical steps to aid in the manufacture of an item or items, usually carried out on a very large scale.

In the context of this document this definition is extended as *a systematic series of operations on different layers of business, social and technological relationships leading to production or manufacturing a value.*
Modern industrial processes feature a great deal of informatization, automation and intelligence. The meaning of the process automation is rather straightforward and self-explanatory. In different industries the automation is either achieved by the usage of automatically operating machines and robots, equipped with computer-based control system. The new concept of informatization is seen in the wide-spread usage of modern information and communication technologies for the purposes of planning and monitoring industrial processes, without necessarily increased degree of their automation.

By intelligence in modern industrial processes often understood an ability of the automation system to adapt to the changing environment conditions through self-configuration and re-configuration as well as its ability to deduct simple logical relationships given the input and output data. In Section 3 an elaborated definition of intelligent automation is presented.

2. IIP challenges in light of international development agendas for future of industrial processes

During the last five years the different international consortia including representatives from the world-wide leading academic institutions, industries and governments have discussed the plans and strategies for the long-term development of the industry. These forums resulted in several developed agendas projecting the industrial development beyond 2030. This document is based on the analysis of the following strategic agendas:


Without a loss of generality the authors conjecture that the main development milestones, requirements and envisioned challenges are similarly formulated in all different strategic agendas. For the purposes of the discussion, we recapitulate several issues from selected agendas which allows to put the requirements under a common denominator.

According to German development agenda Industrie 4.0, the overall goal of the set for the industry is to fundamentally improve the industrial processes involved in manufacturing, engineering, supply chain and the life cycle management. The main driving force of the new industrial revolution according to the Industrie 4.0 vision is the Internet of Things (IoT) and the Cyber Physical Systems (CPS). In the future, machinery, warehousing systems and production facilities will be incorporated using global networks and form a Cyber Physical System. In the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. The final report of the Industrie 4.0
working group defines the major development and research challenges which needed to be addressed to enable the projected development.

Another notable moment is stated in Swedish production 2025 Strategic research and innovation agenda by Vinnova. This document recognizes the current shift of production paradigm from simple production of goods to all-growing role of services connected to products and the associated quality of experience. This paradigm shift requires new methods to shorten the production cycle and capabilities of industries for highly customized production. The key property characterizing the industry of the future is the flexibility across the entire production chain. Vinnova conjectures that new more resource efficient behavior of the consumers will also give a start to completely new business models, which in its turn will affect the production processes. Vinnova’s development strategy identifies the following driving forces behind the transformation of the production industry: individualized production, resource-smart design and production as well as accentuated customer usefulness. The report identifies the research and development challenges which needs to be addressed to meet the demands of the driving forces. Another aspect of the development agenda which makes it outstanding from other similar documents is accentuating the importance of development of new work forms and relationships between workers and the industry. In particular new advanced Human-Machine interactions techniques should be proposed as well as novel methods for efficient development of new skills should be in place in order to achieve the goal.

Figure 1. Intelligent Industries by 2030: Demands and Driving forces.
The result of the analysis of the major research agendas projecting the development of the industries beyond year 2030 is summarized in Figure 1, Figure 2 and Figure 3. It is a common understanding that the current state of the industrial processes could be characterized as globally interdependent, featuring advanced automation and a certain level of intelligence. To this moment the intelligence could be defined as “Engineered intelligence” involving a pre-engineered set of operations of the automation components on different levels, which allows execution of alternative operation paths leading to more efficient performance of the target industrial process. Despite of the truly sophisticated and to a large extend fully automated industrial processes all leading economies univocally conclude that in the current state the industries cannot meet the upcoming societal demands. The major key word commonly identifying these demands is **flexibility**. Flexibility in this context is an ability of an industrial process to adapt accordingly in order to meet the time varying demand on the one hand and a capability to quick reconfiguration in order to increase the quality of the final product and to improve its environmental footprint.

All major strategic development agendas agree on the following driving forces for the future industries:

- Flexible production and manufacturing,
- Integrated operation of the entire value chain for a particular product;
- Resource-smart design and production; and finally
- New work forms and social relationships.

The flexibility can be achieved through yet more advanced automation and intelligence behind the operation and management of the industrial processes. It is a common understanding that the major technology which will advance the industrial processes is virtualization of the machines and their components, the environment and the human into integrated Cyber-Physical Systems. While recognizing the great importance and potential impact of the Industrial and governmental roadmaps and agendas, the authors of this document would like to make a remark concerning the basic definitions. Concerned with future trends, such as the IoT and CPS concepts, most of the documents offer very imprecise definitions that lead to misinterpretation and can bring more harm than value. One shall distinguish the Cyber-Physical approach to the design of computer-controlled Systems, from the vague description of future manufacturing systems as being CPS. Any modern manufacturing system is already a cyber-physical system, because it is “integrations of computation with physical processes”. It already comprises smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently”. Besides, such features as “autonomicity” and “independence of operations” cannot be considered as characteristic of CPS, they would rather belong to “Intelligent Manufacturing Systems”. On the other hand, adopting the “true CPS” view and design approach is capable of bringing numerous benefits to the future industries.
Figure 2. Evolution of industrial intelligence.

Connected to the last remark it is important to characterize the state of the technology in the period in question in order to proceed with the identification of the academic challenges. We also intend to crystallize the definition of “intelligence” depending on the stage of the technology development. These definitions are also summarized in Figure 3. As is stated above by the present time the industry features a great deal of automation. To some extent the current level of automation of the industrial processes allows to talk about certain level of intelligence. The intelligence of most of the modern industries manifests itself through the usage of expert systems for performing root-cause analysis and inferring of observation based process models; neural networks are widely used for classification purposes; distributed planning and execution of alternative operation plans. Since all of the methods require a great deal of engineering by human developers we will call such intelligence “Manual intelligence”.

Already at the present time there is a great trend of adopting service oriented architectures for semi-automatic orchestration of distributed functionality, adoption of agent-based technology for increasing the level of flexibility. We will call this era - the era of “Automated intelligence”. In the opinion of the authors and according to the reviewed research and development agendas realistically this era will span all the way until 2030 when most of the agenda envision full adaptation of the SOA.

Looking beyond 2030, the level of technological development should allow yet higher degree of processes’ flexibility including fully automatic orchestration and consistency verification, runtime automatic re-tasking of machinery and control system as well as industrial machinery learning new tasks by observation. We call this level of intelligence as “Evolving Intelligence”.
Part II. Detailed research roadmap in selected areas of the identified research challenges.

The minimalistic definition of cyber-physical system given in [6] “(CPS) are integrations of computation with physical processes” has given rise to the synergetic system design and analysis methodology that considers both computing and physical processes as two integral parts of one system with complex interrelations between each other that can have substantial impact on their operation and performance. Most if not all of the industrial processes are certainly cyber-physical already (and have been for long time), but approach to their design has not been much following the CPS agenda. In this section we propose a number of steps to bridge this gap to the benefit of the industry based on the analysis of the current trends. The reasoning line of this chapter adopts the top-down approach starting with consideration of the trends and gaps on higher (business relationship) abstraction level descending to the developments on the level of particular software and hardware components (sensors and actuators).

At the highest level we conjecture that industrial automation will remain to be the user (rather than main development driver) of advanced computing platforms initially developed for other application areas, where higher investments is possible due to high-volume production opportunities including military, space, consumer electronics, robotics, automotive electronics, business computing, gaming (See illustration in Figure 4). The authors of this document see the need to monitor the progress in those areas and timely pick and apply promising technologies in the industrial automation context.
It is likely to see the use in industrial automation of such recent inventions as:

- mobile devices with augmented reality (like Google glass);
- modular mobile devices;
- mobile robots (like quadrocopters);
- Gesture steered robots;
- adaptable wireless networks providing acceptable quality of service in noisy environments;
- precise time synchronization;
- wireless sensor networks, in particular, body area networks that can be used as a part of workers uniform in human-machine smart industrial environments.
- dependable networking and embedded computation technologies initially developed for automotive and military applications.
- modeling of user behavior in different social groups.

2.1 Globally integrated industries

Effectively the availability of globally integrated industries by 2030 projected by the main-stream research agendas implies enabling the access to information on all levels of granularity down to every single intelligent component and providing the infrastructure for the efficient management of huge data flows.

As a matter of fact the developments of such kind are currently going on in the scope of Smart Cities (although multiple references exist we refer to a policy document by Euro Commission [8].) In the scope of this document Smart Cities are referenced not only due to a similarity of technical characteristics and requirements as those of globally integrated industries, but also due to availability of commercial solutions from leading IT vendors such as CISCO [9] and IBM [10]. Another relevant activities in this domain are several “City Operating Systems” solutions, including those from Urbiotica [11] and PlanIT [12].

In the opinion of the authors these and similar companies will shape the future development of the computing infrastructure for intelligent industrial processes. Adopting the state-of-the-art techniques from service oriented architectures such companies will eventually standardize the SOA interfaces for industrial interaction.
What currently is not fully understood and it is where the universities could contribute to the ongoing standardization process is the systematization of domain-specific raw data and its conceptualization. The importance of this is proclaimed by Tim Berners-Lee, the inventor of the world wide web [13]. It is essential that this research is conducted in close cooperation with the industries forming parts or an entire supply chain. This is mainly to bridge the cultural gap between the industries and the world of information. Although there are notable examples of such collaborative projects e.g. [14] there is a clear need for a closer interaction with the diverse industrial partners.

Another gap on this level of “intelligence” relates to data acquisition and and data processing. The Cloud Computing nowadays is already mature technology. However, so far the virtualized computing infrastructures are very rarely (if not at all) used as part of control loops. The current state of the cloud technology could be somewhat compared to initial versions of the world-wide web having humans as final consumers of the information. **By connecting the “Intelligent industries” the size of the information flows, the demand on the computational power, the requirements on the dependability and sustainability of virtualized computing infrastructures will increase dramatically.** In the following sections particular gaps in the areas of data acquisition and virtual computing infrastructures are discussed.

### 2.1.1 Data Acquisition

The clear trend is widespread penetration of wireless sensors, mobile devices, Cloud-services into the factory floor. The controllers are getting more decentralized and networked. This trend will certainly continue in the years to come, leading to the situation when all sensors and actuators will become intelligent, network connected and providing rich semantic data rather than merely signals. This will provide seamless access to any process related information (measurements) and its integration with process models in real-time, enabling more accurate control and reconfiguration of processes.

The authors of this document conjecture that the new forms of traffic should be natively supported by operators of wireless broadband communications. In order to enable this it is of primary importance to conduct research on adaptation of LTE-A architecture to machine-to-machine communications in general and the specifics of industrial communications in particular. On a high level of abstraction the challenge for the developers and vendors of LTE technology is to enable mobile operators as the first tier data aggregation service providers. Specifically, LTE networks should natively support access to individual machine components either by including technology-specific gateways in the architecture or even providing direct broadband access to the individual sensors. A set of particular research challenges is discussed in [21].
2.1.2 Virtualized computing infrastructures

The cross-sectoral gap to be bridged on the way towards enabling mobile operators as part of the m2m data processing loop is the historical barrier between the computing and telecommunication industries. Traditionally these industries followed parallel development paths. Today, however, the borders between the computing and telecommunication technologies are disappearing, we are witnessing a convergences of the two sectors. Only at the end of 2010 large mobile operators [22] and leading vendors of telecom technologies initiated adoption of recent trends in management of computing infrastructure for optimizing own infrastructures. As the trend is still new there is a great demand on understanding the technological and scientific principles for future converged architectures. Therefore the main scientific objective before 2030 and further on is to establish and foster a common research agenda on the intersection of the two sectors. It is of ultimate importance to address a cultural gap between different branches of engineering science contributing collectively to the development of large-scale distributed computing and communication systems. Traditionally research on infrastructure optimization, quality of data services and fault management of large-scale infrastructures and security is conducted separately. This makes the resulting solutions often sub-optimal by not accounting for performance-limiting factors introduced by the adjacent technologies. Referring back to Figure 4 it is of particular importance to introduce another direction into the optimization process. The automation procedures for achieving higher degree of energy efficiency should be codesigned with the optimization procedures of the virtual environments which have an objective of performance optimization of quality of virtual services.

2.2 Flexible factories

Flexibility of factories in general and their production floors in particular should be enabled already at the design stage. An extensive state-of-the-art survey in the area of the design of automation of industrial processes is in [7]. The most important impact of the CPS concept is cultural: In the pre-CPS era, there
always has been a substantial cultural gap between process engineers designing the physical process and designing the cyber part (control and automation).

The process and control engineers have been using accurate modeling of processes, but had little understanding of computations specifics in the embedded devices, using very coarse grain computation models (e.g. PLCs). On the other hand, embedded systems engineers were focusing on computational performance and dependability of embedded controllers, but used the “environment” abstraction of the world outside the computer that lead to substantial difficulties in achieving the required system properties, such as robustness.

The CPS approach implies the cross-penetration of knowledge and design approaches between these, previously separated domains.

The system engineering practices of industrial automation systems experience the influence from:
- simulation and virtual reality, gaming
- best practices in software engineering domain (UML, SysML)
- Internet and IoT

2.2.1 Simulation

Modeling, analysis, and simulation are essential for understanding complex systems such as CPS. This is widely recognized by Universities, research institutes and industrial groups around the world. The creation of reliable multi-disciplinary simulation tools that can be used to support the entire development process has been identified as a major scientific goal in several research roadmaps and agendas for the coming 15 years. The research efforts in this domain should be directed towards enabling creation of simulation technology, which will be used daily throughout the engineering life-cycle (e.g., research and development, marketing, concept study, detailed design, testing, operation, product updating, problem solving, maintenance, operator training).

A strong evidence of the cyber-physical approach getting recognized and adopted in industrial automation is the growing popularity of the “simulation in the loop” approach to systems validation. This approach implies availability of accurate simulate models of the uncontrolled plant behaviour that can be connected to control systems through open interfaces and used instead of the real plant for control system debugging and performance estimations.

The availability of the simulation models as “commodity” will be a great enabler of this approach, leading to higher quality designs achieved in shorter time and at lower costs. It may also lead to wider application of the “parallel” systems approach, when a simulation model of the plant is executed in parallel with its real operation and can be used for finding more optimal scenarios of operation without disturbing the production process.

2.2.2 IoT and data driven dynamic SOA

The impact of the Internet and Internet of Things on the engineering process is seen in the adoption of Service-oriented Architecture that implies design of systems as decentralized nodes offering well-defined service interfaces. IoT is seen as enabler of Intelligent Product concept, of higher quality and traceability.
The authors of this document remarks that a Service-Oriented Architecture by itself does not make any process more flexible if the underlying process is not flexible by itself. **A high degree of physical modularization and decentralization in control procedures should be developed along with the definition of the suitable SOA interfaces.**

![Image of modular mobile telephone by Google.](image)

**Figure 6.** The latest model of modular mobile telephone by Google. This analogy is used as an example of an agility of a complex software-hardware system, which makes its reconfiguration inherently simple.

Again referring to projections on the development of the world wide web by its creator [13] the main challenge is facing the computing systems of the future is to efficiently derive meaning out of huge amount of raw data. In the case of Intelligent Industrial Processes the meaning shall be defined in terms of models which describe complex interactions within the system of systems of different scale. In this respect classical formulation of data mining as finding patterns in vast amount of data should be extended by problems of inter-relating the patterns into structures suitable for automatic taking of decisions. During recent years the advances in the computing platforms and communication systems boosted the interest in applied methods of artificial intelligence on the new level.

Artificial intelligence is a mature area of science and engineering with multitude of methods being used in practical applications [15]. In the context of the IIP three major classes of systems are of particular interest since they found their applications for management of processes control [16, 17, 18] as well as the management of large-scale telecommunication networks [19]. These are Rule-based systems, Case-based event correlation, and Probabilistic event correlation.

A typical rule-based system contains a set of “IF-THEN” statements of diverse hierarchy. It is typically constructed by a knowledge engineer to cover a particular domain, e.g. fault management for a particular plant. An obvious drawback of this approach is inflexibility in adapting to changing conditions. In management domains with dynamically changing properties such systems must be redesigned, reflecting the changes in the new set of rules.

The probabilistic approach performs event correlation accounting for uncertainty using solid mathematical foundation of Bayesian reasoning. One of the main criticisms of Bayesian reasoning is the difficulty of coming up with prior probabilities before computation begins.

A case-based (CB) event correlation system solves a new problem by remembering a previous similar experience and adapting the previous solution to the specifics of the new problem. A case-based event correlation offers several distinct operational features. Firstly, a case in CB can be a semantically rich data
structure, thereby making it ideal for management tasks dealing with complex problems. Secondly, the case adaptation algorithm used in CB systems makes this approach more suitable for solving problems where the exact solution either does not exist or is too costly. Finally, being by nature a learning system, CB allows the operational behavior of the event correlation process to be improved without additional hard-coding [20]. The main technological challenges, which so far prevented the usage of CB methods for temporal reasoning, are problems with semantic analysis of alarm information due to the lack of a common standard for semantics of alarm representation and low performance of the current event correlation algorithms for performing spatio-temporal analysis on masses of events.

In their recent publication [20] the authors overview the progress of the event correlation techniques and provide a set of recommendations for future development of event correlation techniques in the context of system management:

1. The next generation event-correlation systems must be able to deal with uncertain knowledge.
2. Better learning techniques to improve the accuracy of case-based systems
3. Faster algorithms based on binary vector mapping which would convert a problem of correlating spatiotemporal events from complex cross-matching of “IF-THEN” rules into binary vector mapping operations.

2.3 Security is the key to IIoP emergence

Traditionally the importance of security is often underestimated both by the operators and research groups focusing on optimization of functional block. As a result it is treated as a costly add-on rather than a mandatory property. The security challenges of modern ICT systems are complex and should take into account complex relationships between people, data, applications and the infrastructure. In order to address these challenges radically new integrated security solutions are needed. The main shift of paradigm in designing security components should be to divert from “reactive” approach towards more “proactive” deploying sophisticated methods for situational awareness. A good overview of the security challenges and a roadmap for addressing them is provided in IBM Security Strategy [28]. One of the key theme in the agenda is deeper integration of security intelligence through an improved usage of analytics. The analytics in turn should be leveraged by the advances in the area of artificial intelligence.

2.4 IIoP are human-centric

It would be wrong to think that intelligent industrial processes assume diminishing the roles of human workers in operation. Although “Intelligence” of the processes implies the all-increasing degree of automatization, the humans will not be excluded from the loop in the foreseeable future. Instead IIoP places new demands on the skills of the human operators and work forms on the one hand and should address the demands and expectations of the human resources on the technology and the new worker-industry relationships on the other.

Here it is of ultimate importance that the concept of IoT and CPS are not purely technical, they are centered around humans and treat humans as the native part of the cyber-physical socium. The main technological enablers for a deeper integration of humans into a CPS are embedded devices, mobile gadgets, smart clothes and service oriented architectures.

Using mobile devices, work activities can be computerized and automated outside of the actual offices and
independent from the workers location. Mobility of resources, from this point of view, increases the productivity of the organizations via using out-of-office workplaces and thus it is attractive to the modern organizations. Moreover, mobile devices are equipped with tools such as camera, voice recorder, etc., and are capable of sending and receiving data over communication networks, which enables them to communicate with other devices (e.g. sensors) as well as data processing and data analysis systems (e.g. image processing, data mining and machine learning systems). All of these state of the art technologies and equipment can be utilized to acquire and analyze real-time information from the context of an environment, which in our case is an industrial plant [26, 27].

The main challenge to address in the years to come is to demonstrate how control and supervision of production plants can be enhanced by the use of mobile wearable devices utilizing automated knowledge engineering. This will require developing the critical mass of technologies enabling more efficient supervision and maintenance of industrial plants by distributing the functionality of control room across wearable mobile devices of the personnel and assisting their operation with a set of services based on automated knowledge engineering.

2.3.1 Educating the next generation of CPS-enabled specialists

While in general modern students are highly technology-aware, a more systematic approach to education of future specialist of Intelligent Industries is needed. Specifically Intelligent industries will call both for the diverse knowledge of the CPS ecosystems as well as a quick refactoring their skills. The traditional engineering educations needs to be upgraded in order to leverage the specialists of the required quality.

Dependability of a computing system in general is an integrated system property jointly characterized by: security, reliability, availability and manageability. The ultimate importance of advancing the theories and foundations for highly dependable, scalable ICT systems, methods for verification, validation and implementation of such systems based on fault tolerance, controlled degradation and self-healing is recognized on transnational level [25] as well as by the major players in the respective industries. Learning how to design highly dependable distributed systems is hard due to the inter-disciplinary nature of the problem. Traditionally education in Europe rather narrow-focused with relatively small insights into a “bigger picture”. This situation is not by any means unnatural taking into account a large range of adjacent topics. Nevertheless, it becomes more and more evident that the improvement should happen through more evident links to the particular industrial needs and proper attention to the innovative side of the education.

The problematic of educating specialists of the future Internet of Things is nowadays very hot in industrial countries. Amongst recent education activities targeting this objective are works from the Open University in the UK [23] and Luleå University of Technology [24]. As one of the challenges the university should face on the way towards enabling the IIP industries the authors highlight the importance of development dedicated BSc and MSc specializations as well as entire graduate schools consistently focusing on providing the holistic picture of the cyber-physical systems and the Internet of Things.
2.4 Summary of research challenges

The discussion on challenges the universities and the industries are confronting towards enabling Intelligent Industrial process vision is summarized below on the per high-level objective basis.

- Cross domain knowledge adoption and transfer
  - military, space, consumer electronics, robotics, automotive electronics, business computing, gaming.
- High level objective 1: Globally Integrated Industries
  - systematization of domain-specific raw data and its conceptualization.
  - provide seamless access to any process related information (measurements) and its integration with process models in real-time, enabling more accurate control and reconfiguration of processes.
  - adaptation of LTE-A architecture to machine-to-machine communications in general and the specifics of industrial communications in particular. On a high level of abstraction the challenge for the developers and vendors of LTE technology is to enable mobile operators as the first tier data aggregation service providers.
  - bridge the cross-sectorial gap between, data, telecom and automation industries by homogenizing the design and development principles as well as developing methods for joint analysis and optimization.
- High level objective 2: Flexible factories and processes
  - enable co-design of processes and supporting services.
  - observation based (learned, deduced) models of systems of systems accounting for operators’ actions.
  - dynamically evolving SOA based on run-time deduced models.
  - flexible programming languages allowing for (semi-) automatic re-tasking of functional components.
  - simulation technology, which will be used daily throughout the engineering life-cycle.
- High level objective 3: Secure IIP
  - Enable an integrated security across human, data, application and infrastructure axis.
  - Wider usage of advanced methods for data analytics to leverage proactive security.
- High level objective 3: Human-centric IIP
  - Enable the "worker-as-a-service" vision.
  - Develop tools and education programs for CPS aware specialists for future IIP industries.
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