

# Synergies of Operation, Information, and Communication Technology for Solving New Societal and Industrial Challenges



## Future Directions

WENBIN DAI<sup>ID</sup>, PAULO LEITÃO<sup>ID</sup>,  
KIM FUNG TSANG<sup>ID</sup>, YANG SHI<sup>ID</sup>,  
GERHARD HANCKE<sup>ID</sup>, LEI SHU<sup>ID</sup>,  
MORIS BEHNAME<sup>ID</sup>, JAN HAASE<sup>ID</sup>,  
and VALERIY VYATKIN<sup>ID</sup>

The world is facing a series of new societal and industrial challenges, such as continuously increasing costs in food and energy supply and a short supply of skilled labor. To solve these new challenges, operation, information, and communication technology is entering a new era with more focus targeted to cost reduction and energy savings. In this article, how innovative technologies including virtualization, low-code development, digital twins, and industrial agents can support and impact digital and green transitions is analyzed. In addition, how these technologies will help the security and sustainability of future industrial automation systems is also discussed.

### Introduction to Challenges in Industry by 2025

The world is facing a series of new societal and industrial challenges. The consequences of the global pandemic and the continuing war have seriously affected the food and energy supply all

over the world. The global supply chain and manufacturing facilities are moving to places with lower costs and cheap labor, which also affects the manufacturing domain. First, the labor cost has kept increasing during the past years for all industries [49]. The salary for IT engineers is usually much higher than that for automation engineers, which leads to a shortage of young automation engineers in the production industry [50]. Second, the global recession will cause high inflation [35], and the continuously increasing cost of raw materials and resources will bring huge challenges to manufacturers. The delivery time of automation products is delayed to several months or even more than a year. Third, the volume and availability of the generated data from the shop floor have dramatically increased because of the digital transformation of factories. How to use these data to improve efficiency and reduce costs becomes a very important task for manufacturers to remain competitive in the market. Finally, the growing importance of decarbonization, green

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transition, and circular economy, need to prevent a global climate disaster, introduces totally new requirements to both the IT and the production sectors.

On the other hand, the Industrial Internet-of-Things (IIoT) provides connectivity between field devices and massive computing power and storage in the cloud. Industry 4.0 enabled massive customized production for manufacturing systems based on IIoT, data analytics and intelligence, human-machine interaction, additive manufacturing, etc. Humans are first considered as a part of the digital workflow in manufacturing systems introduced by Worker 4.0/Operator 4.0 [1]. In addition to Industry 4.0, the European Commission introduced the concept of Industry 5.0, which suggests industries to lead the digital and green transition to remain the engine of prosperity under the economic and societal transitions that we are currently undergoing [2]. To solve these new challenges, operation, information, and communication technology (OICT) is entering a new era with more focus targeted to cost

reduction and energy savings, as well as enabling a higher level of intelligence with the human-centric closed loop in consideration.

As shown in Figure 1, key technologies from operation, information, and communication domains for supporting digital and green transitions, including embedded virtualization, low-code development, digital twins, and industrial agents, are analyzed individually, which covers the entire life cycle including the design, development, deployment, and operation stages. In addition, the security and sustainability requirements of future industrial automation systems are observed in the section “Security and Sustainability Challenges in Industrial Internet.” Finally, the potential applications and impacts of synergies of new technologies are discussed.

### Virtualization Technologies in Industrial Internet

Industry 4.0 introduces more stringent requirements on the IT infrastructure. The computation platforms, e.g., cloud and edge computing, should provide possibilities to scale the services up and down based on the needs, opportunities to run software services on different machines, efficiency in terms of computation resource usage, and finally, timing predictability required in many industrial application domains. High-performing cloud and edge computing is built on a virtualized infrastructure technology to maximize resource utilization and, consequently, lower the overall costs. Shared resources (like processors, storage, and network) are pooled to provide software services with virtual machines (VMs) that match the required features. Furthermore, virtualization technologies enable the decoupling of software applications from the hardware (HW) resources, thus providing execution flexibility. Finally, virtualization provides means to control the access to computer resources, for example, the CPU and networks, necessary to meet the predictability requirements.

Solutions to support predictable virtualization have been applied to both hypervisor-based and container-based

virtualization by integrating real-time scheduling algorithms at the cloud/edge node level to schedule VMs and inside each VM to schedule threads/tasks that run services [3]. In addition, models based on hierarchical scheduling have been adapted to configure VMs statically.

Many industrial systems might require dynamic resource management due to changes in resource availability and workload. For instance, the available resources might change due to changing/upgrading computers in the cloud and edge, while the workload might also change over time. To maintain the required QoS and predictability level, resources assigned to VMs should be adapted in response to changes in resource availability and workload changes.

The closed-loop control approach as an adaptive solution is used to manage dynamic changes that affect the timing performance of the software services. Controllers are used to assign sufficient resources to VMs based on their immediate needs. The adaptive solution-based approaches have been realized in widely used cloud infrastructures; for instance, the authors of [4] propose dynamic management of VMs based on resource usage over time implemented in OpenStack, and the authors of [5] propose a framework for adaptive resource allocation and dimensioning for real-time containers implemented in Kubernetes.

Recently, there has been increasing research interest in using digital twin technologies for monitoring, controlling, and optimizing computing resources using simulation and machine learning-based solutions. Such a closed-loop control solution provides advanced capabilities compared with traditional ones while introducing higher complexity. For instance, Almasan et al. [6] have proposed a network digital twin concept to control and manage communication networks efficiently. Another example is using digital twins for mobile edge networks in 6G [7] to orchestrate the network and provide intelligent and optimal decisions. Furthermore, the work presented in [8] shows how digital twins can be used

to optimize communication, computation, and caching resources targeting mobile edge computing. Connecting computing resource digital twins with physical factory/machine digital twins would enable holistic optimization. For example, production plans would be optimized based on the availability of computing resources.

Realizing the computing digital twins requires efficient controlling of resource usage and accurate models of how VMs, running software services, use the resources. However, most of the existing virtualization technologies orchestrate VMs based on the CPU time/communication bandwidth,

which might not be sufficient for guaranteeing predictability and high performance. Ignoring other resources, such as memories, caches, internal buses, and translation lookaside buffers, might significantly impact performance and predictability [9].

Fortunately, the usage of different computer resources by software applications can be monitored using the performance monitoring unit (PMU) provided by most modern HW. PMUs provide essential information for modeling and controlling resource usage. For example, throttling VMs that generate too many cache misses can limit the impact on the other VMs that share

the same level of caches [10]. The performance counter also allows dynamically partitioning the cache among VMs based on their actual needs [11]. Figure 2 shows a framework that integrates PMUs in the orchestration of VMs that is inspired by the work in [12], which would be essential for realizing digital twins.

### Low-Code Development for Industrial Internet and Edge Applications

With the increasing size and complexities of the IIoT system, the software development and deployment time are dramatically increasing due to

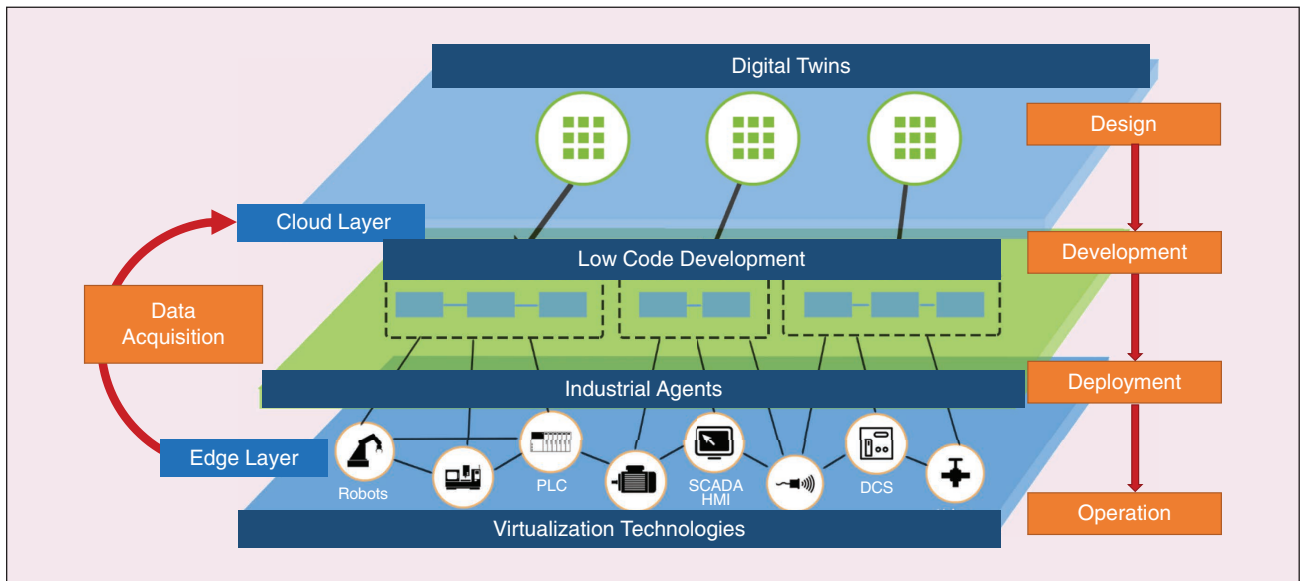


FIGURE 1 – OICT for digital and green transitions. PLC: programmable logic controller; SCADA: supervisory control and data acquisition; HMI: human-machine interface; DCS: distributed control systems.

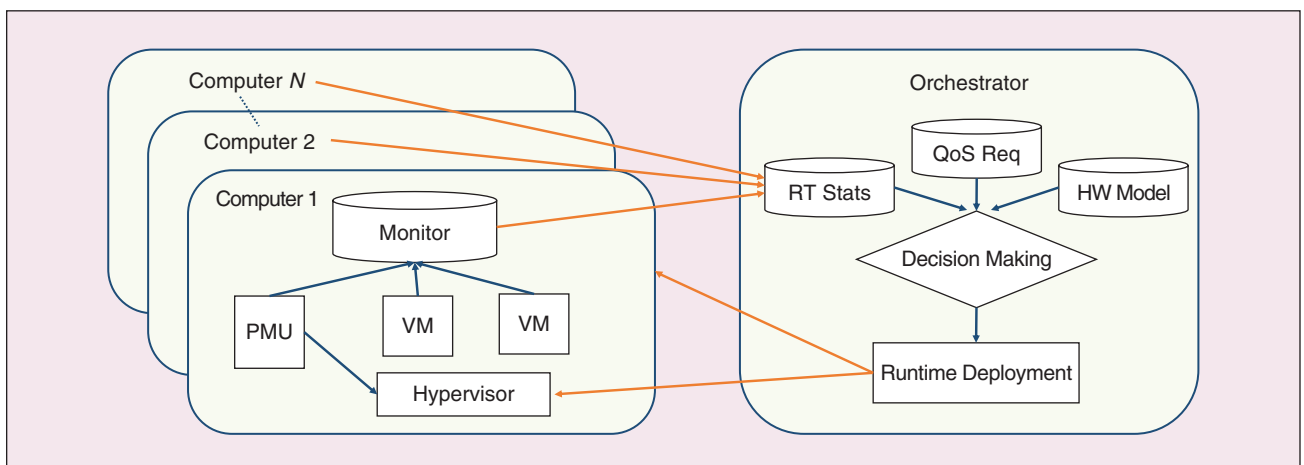


FIGURE 2 – A framework for online resource management [6]. RT: real time.

handling interoperability, reusability, and pervasiveness among various devices. Low-code and no-code development are heavily linked with automatic code generation and model-driven engineering (MDE). By abstracting domain-specific conceptual models, MDE emphasizes models as the primary software development artifacts.

The basic principle of MDE is “everything is a model” [13], which is to create different levels of abstraction and connect them to form a complete system model. Automatic code generation is achieved by converting abstract models to detailed code using model transformation techniques. As the most popular modeling language in software engineering, the Unified Modeling Language (UML) has been widely adopted for visualizing, specifying, constructing, and documenting artifacts of software-intensive systems, as well as code generation. For instance, programmable logic controller (PLC) code (structured text and ladder diagram) can be generated automatically from UML models created by UML tools [14] and the Simulink PLC coder [15]. Similarly, Siemens has widely applied its Mendix low-code development platform to create more than 100 applications and build numerous solutions in the past year. The Mendix platform is fast becoming the core of the cloud services in Siemens’ Xcelerator portfolio of software and services [16].

The MDE has already been successfully applied in the automotive industry; for example, the AUTOSAR architecture is used by Audi and other manufacturers for describing vehicle functions as platform independent [17]. The MDE approach and the AUTOSAR standard are also adopted by Siemens for providing highly integrated design, development, verification, and validation processed in their PLM software that is used by Mercedes-Benz, Volkswagen, and other car manufacturers [18]. These complex models can also be modeled and managed in a heterogeneous way to provide an abstract view of the entire system design. For example, a temporal model is introduced by Lohstroh et al. for describing

## How to use these data to improve efficiency and reduce costs becomes a very important task for manufacturers to remain competitive in the market.

various domains and their deterministic coordination across multiple timelines [19]. Metamodels are commonly used for managing heterogeneity. Generic metamodels are created to facilitate mappings and transformations among heterogeneous models from conceptual models to data-driven models by Jarke et al. [20].

One major challenge of automatic code generation for smart manufacturing is to obtain detailed physical models for complicated processes. These models provide simulated feedback data by using closed-loop testing and verification with control software. The data generated during the manufacturing process are increasing dramatically with a millisecond-level update rate in industrial applications. With IIoT support, the challenge can be addressed through data-driven model recovery methods. Taking advantage of the expert knowledge and information acquired from feedback data will facilitate new strategies in controlling the manufacturing process, such as machine fault prediction and cost estimation.

With artificial intelligence (AI) and industrial big data support, data-driven automatic code generation based on machine learning has become a popular topic in recent years, as shown in Figure 3(a). One common approach is to adopt the abstract syntax tree (AST). The AST is a tree representation of the abstract syntactic structure of source code, which is commonly used in compilers. A data-driven syntax-based neural network model is proposed for code generation, which obtained the syntax model of the target programming language as an AST and transformed natural language into the target programming language based on both syntax and requirements [21]. The underlying syntax of the target programming language introduced as prior knowledge results

in higher accuracy and efficiency in automatic code generation. In this approach, cloud-edge collaboration plays an essential role to provide sufficient computing power and storage space for such AI-based data-driven code generation. With the development of transformer-based large language models [22], data-driven code generation has reached a completely new level. Perez et al. used pretrained large language models [generative pretrained transformer (GPT)] for generating Python code from natural language requirements [23]. Brennan and Lesage explored the possibility of applying OpenAI Codex for generating equivalent code in high-level programming languages such as Python and C from IEC 61131-3-based PLC code [24]. The results show that the GPT-based generation can provide insights for Industry 4.0 programming solutions.

### Digital Twins in Industrial Internet

Cyber-physical systems (CPSs) consist of a physical part and a digital part. In many cases, it might be very helpful to have an exact representation of the physical part of the digital world to be able to react to physical influences, movement, or damage. For this, a digital twin comes into play [25]: a digital twin is a virtual model that precisely reflects the physical object. To achieve this, sensors are deployed, which can measure environmental values such as pressure, temperature, acceleration, spatial alignment, poses, etc. These sensor values are then evaluated and interpreted, enabling the system to exactly copy and visualize the physical object’s status in the digital world. Based on these data, it is then possible to simulate possible outcomes if specific system parameters are changed: performance issues can be analyzed, and changes to improve the system can be monitored in the digital world first.

## Connecting computing resource digital twins with physical factory/machine digital twins would enable holistic optimization.

There are several types of digital twins, and they are usually distinguished by the level of magnification when focusing on the system. The first is process twins, monitoring a whole production facility. They can help optimizing production timing schemes for the seamless work of components. An example might be different production robots at a production conveyor belt, which are to be synchronized to maximize productivity. The next level is a bit more focused on the collaboration of two systems, such as two production robots passing a workpiece from one to another; this is called a unit twin. Farther along the magnification line, the next level would be the asset twin, giving insights into the interactions of different components in one system. This could be the digital representation of the status of one production robot with its arm, the current position and pose, and all its joints and hinges. The last level would be covered

by a component twin: it shows the current status and activity of a specific component, such as the exact position and current activity of a robot hand.

Apart from visualizing the current status of a physical object, it is also possible to use actuators to do the reverse: changing the status of the digital copy and then controlling actuators to mimic changes also in the physical world. This is particularly helpful if a simulation of a system parameter change turns out to be beneficial in the digital world and is then to be applied back to the physical object. A significant benefit of such simulations is the fact that they are fed with real-world values all the time and can thus easily adapt to any unforeseen change or outcome. To have a precise representation of the physical world, faulty sensors are to be identified, isolated, and quickly replaced [26]. Furthermore, digital twins may be located at long distances away from

the physical object. This way, control centers can manage many physical objects at once and even monitor and control the interactions among physical objects. Such communication is to be made secure [27].

Digital twin technology is based on the first-principle model, a mathematical algorithm that simulates the performance of a device; the physical process feeds input (i.e., sensorial data) into the algorithm, which calculates a digital representation of the real-life situation. A good example of the digital twin utility is the wind turbine, as shown in Figure 4. The physical object is outfitted with many sensors, tracking the outside temperature, wind speeds, rotation speed, energy output, and several more. When strong gusts in stormy weather threaten to damage the wind turbine, it has to be shut down and secured when the wind speed reaches the cutout speed (which denotes how fast the wind turbine can rotate before it risks damage from further operation) [28]. Digital twins are thus a convenient way to interact with the physical world by changing the digital world related to it.

Digital twins are used for the detection of damage, as well as the prediction

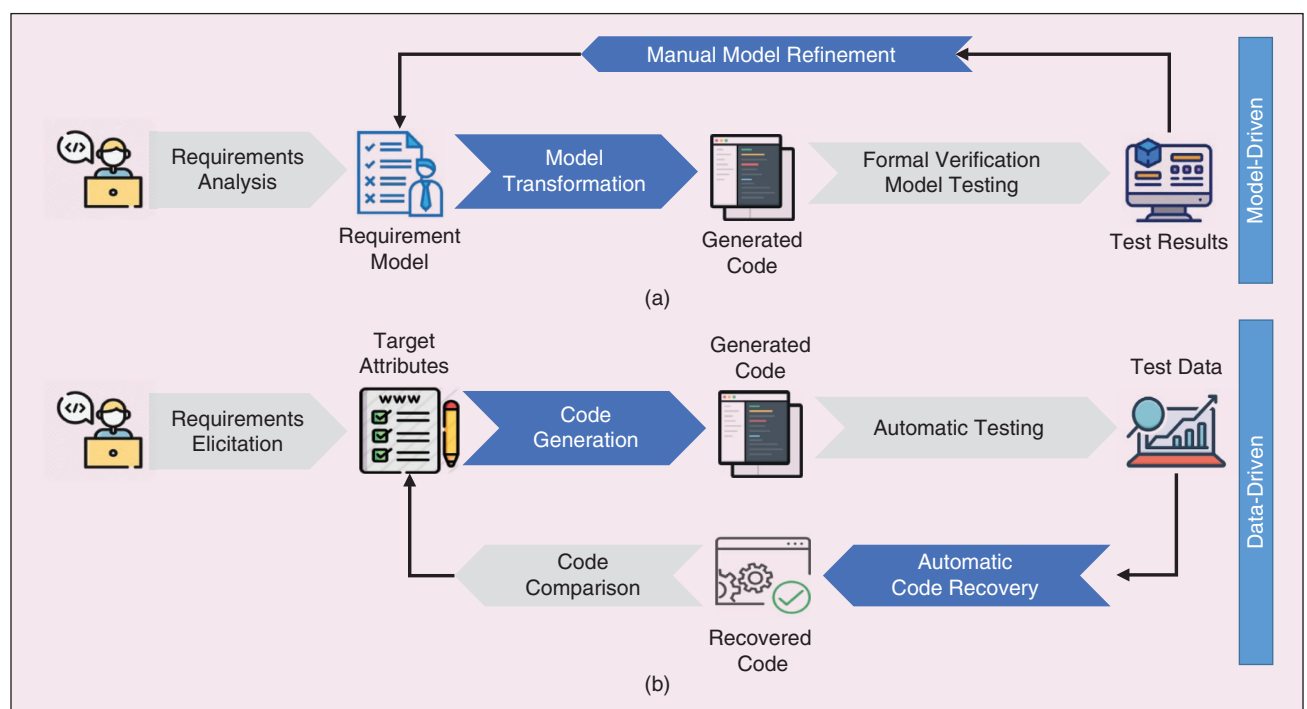


FIGURE 3 – The (a) model-driven versus (b) data-driven automatic code generation for IIoT.

of future performance decrease. In this way, the approach of predictive maintenance [30] takes current sensor data and historical data into account to predict future failures or catastrophes long before they occur. This way, countermeasures can be brought up to avoid the upcoming problem entirely. A commercial example showing digital twins for predictive maintenance is described in [46], namely, the maintenance tasks for the Köhlbrandbrücke depicted in Figure 4.

There are tendencies to bring companies working with digital twins together,

## The results show that the GPT-based generation can provide insights for Industry 4.0 programming solutions.

namely, the Digital Twin Consortium (DTC) [31]. The idea is to have an open platform to work together, discuss future developments, agree on standardization issues, and find possible partners for joint projects. Not only academia but also many practitioners from big and small companies are present in the DTC.

This way, the development of a multitude of proprietary and incompatible approaches can be avoided, and even smaller members can exert influence on further designs and trends.

### Industrial Agents for Industrial Internet

A prominent example of industrial intelligence supporting technologies is the multiagent system (MAS). It is classified as one distributed AI technique, which is based on a set of autonomous and cooperative entities, called agents. In such systems, physical or logical components (e.g., a robot, machine, product, and order) are represented by agents. Each agent possesses local knowledge and skills and a local perspective of their surrounding world. As illustrated in Figure 5, the agent is able to sense and act in its environment, reason over its internal states to aim for its goals, and communicate with other agents. The global system behavior emerges from the interaction



FIGURE 4 – A visualization of the digital twin of the Köhlbrandbrücke. (Source: copyright SMART-bridge Hamburg, taken from [29].)

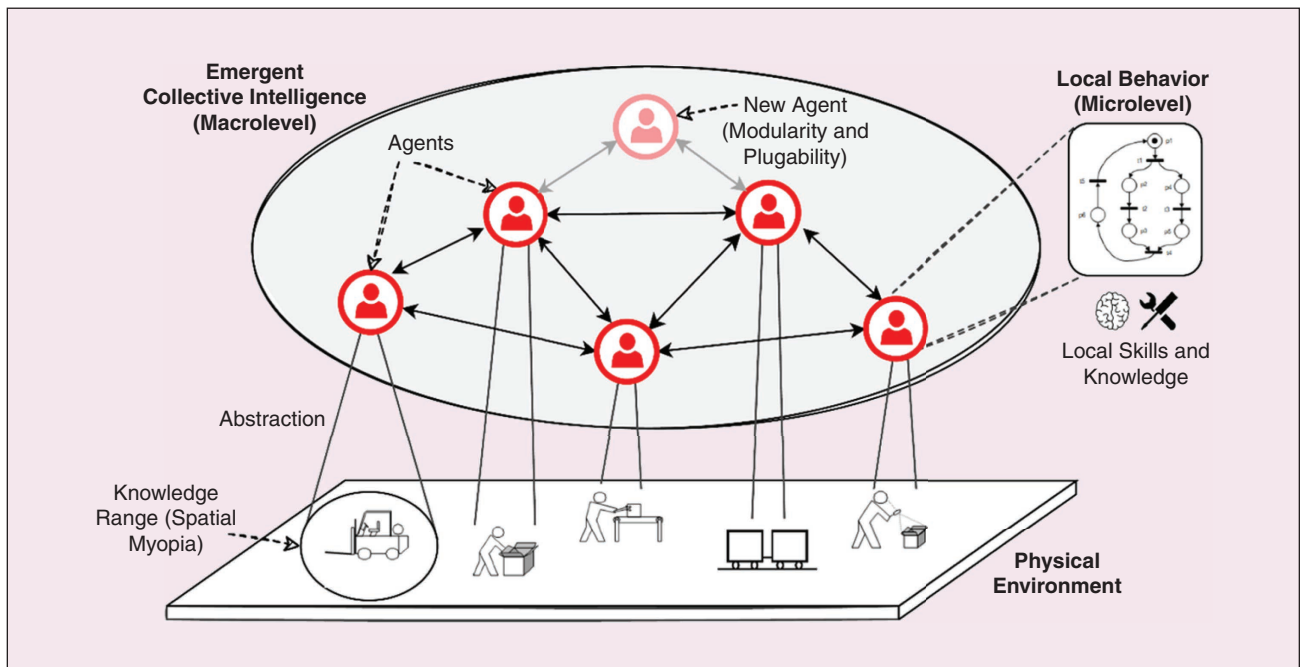


FIGURE 5 – The basic features of an industrial agent-based system [38].

**A significant benefit of such simulations is the fact that they are fed with real-world values all the time and can thus easily adapt to any unforeseen change or outcome.**

among individual agents, through the implementation of distributed collaboration and negotiation strategies. Each agent contributes with its knowledge and skills, and the decisions are taken in a decentralized manner.

The MAS offers an alternative way to design complex systems based on the decentralization of functions [32], providing modularity, flexibility, robustness, pluggability, loose coupling, adaptability, and reconfigurability on the fly, as also illustrated in Figure 5. This overcomes the typical problems exhibited by the traditional centralized, rigid, and monolithic control structures that are not enough to address the current requirements imposed on industrial systems.

Industrial agents inherit the software agent principles, e.g., intelligence, autonomy, and cooperation, but their application domains are related to industrial environments and need to address specific requirements for industry, namely, specific HW integration, reliability, fault tolerance, scalability, industrial standard compliance, quality assurance, resilience, manageability, and maintainability [33]. Being applicable to industrial applications, an industrial agent, recalling the holonic principles, has usually an associated physical HW counterpart, which increases the deployment complexity, particularly due to the interface with heterogeneous physical counterparts, which are usually implemented in different ways, following proprietary or more standard technologies. The IEEE 2660.1-2020 standard [34] defined a method to recommend the best interfacing practice for a particular application scenario considering the feedback from experts in implementing and using different interfacing technological practices.

During the last 20 years, industrial agent technology has been adopted in

several sectors, namely, production, logistics, and energy, to develop collaborative and intelligent solutions [32]. In spite of being applied for a wide range of industrial applications, the emergence of industrial CPSs (ICPSs) in the context of Industry 4.0 constitutes an opportunity to improve its visibility and importance. Particularly, industrial agents strongly contribute as a key enabling technology to realize ICPSs, concretely to enhance the functionalities provided by the digital twin concept and the asset administration shells (AASs) defined in the Reference Architecture Model Industrie 4.0 [36], which play an important role in the development and implementation of Industry 4.0 components. The AAS enables information exchange among industrial agents that is mainly implemented based on Open Platform Communications Unified Architecture information models [37].

In fact, the use of industrial agents allows for distributed control and intelligence capabilities among a network of intelligent nodes that are distributed along the edge–cloud computational layers covering the IT dimension, through embodying intelligence and collaborative models in AASs to support decision-making in ICPSs. Combining the autonomous and cooperative characteristics that software agents can provide with machine learning capabilities can further lead to solutions that deal better with monitoring, diagnosis, prediction, planning, optimization, and control, which are fundamental characteristics of ICPSs. Additionally, since simulation plays an important role in digital twin approaches, the use of agent-based modeling and simulation can contribute to better monitoring, managing, and controlling large ICPS infrastructures, hiding complexity and in parallel offering self-management and self-optimization.

## **Security and Sustainability Challenges in Industrial Internet**

Information and communication technology (ICT) on sustainability is facing challenges such as information security, divergences between regions and times, and quantification of impacts, while measures are being developed to overcome such challenges.

Generally, a cyberattack can be considered as a category of actions exploiting the system's vulnerabilities and then harming the system, which can be malicious or unintentional. As introduced in [39], there are five main categories of attacks from the perspective of control: denial of service attacks, replay attacks, false data injection attacks, zero dynamics attacks, and covert attacks. There are also other attacks related to information security, such as compromised key attacks and routing attacks. Despite the different attacking mechanisms, these cyberattacks focus on the integrity and availability of the data, thereby aiming to degrade the overall performance and even destroy the stability. Recently, a new category of cyberattacks related to data confidentiality has received increasing attention. The focus of confidentiality attacks lies in stealing secret system information instead of damaging the system [40], [41]. A typical confidentiality attack is an eavesdropping attack. In fact, in practical ICPS applications, cyberattacks become increasingly complicated. Focusing on only one perspective of integrity, availability, and confidentiality may be insufficient to ensure the security and safety of the overall system. A generic security framework with joint consideration of physical components and cybercomponents in ICPSs is of incremental urgency and paramount importance.

The security issue has been widely studied in computer science, and many effective solutions to computer network issues have been reported in the literature. For example, a data aggregation strategy is presented in [42] for data privacy preservation and secure packet transmission. The existing Internet security technologies mainly focus on networking security but rarely consider the security related to

physical systems. Due to the complex interaction between the communication and real-time control subsystems in CPSs, the security issue becomes much more complicated. Protecting network security cannot meet the requirements of security in CPSs. Therefore, it is desirable to ensure the security of CPSs from both control and network perspectives [43].

Many research efforts have been made in the literature to explore the defensive strategies against cyberattacks, which can be mainly categorized into three groups: the protection-based methods, the detection-based methods, and the resilient control-based methods.

For the protection-based methods, the security of the CPS is guaranteed by protecting the identified critical sensors, where the measurements of these critical sensors are encrypted to achieve secure transmission (e.g., [39] and [44]). However, these protection-based methods may reduce the system redundancy due to the use of trusted data only from protected sensors. In addition, these methods may be insecure since the protection may be penetrated by attackers, e.g., malicious internal users. Although the protection-based methods have the aforementioned drawbacks, it is still necessary to ensure the secure transmission of a basic set of measurements to enable the defense against cyberattacks.

The detection-based methods aim at protecting the CPS by detecting maliciously altered signals, isolating the attacked subsystems, and restoring the system to normal mode as soon as possible. Based on the properly designed detection mechanism, the existence of the cyberattacks can be detected, and the maliciously altered measurements can be localized and identified by analyzing the raw measurements [47]. As introduced in a survey article [48], the solutions to the design of detection and isolation mechanisms in the literature include observer-based methods, consistency analysis methods, watermarking methods, baiting methods, and learning-based anomaly detection methods.

The resilient control-based methods focus on making the CPS resilient

## With more people realizing the significance of sustainability and taking action, these solutions will only be more widespread and mature.

against cyberattacks [45]. The resilience of the CPS indicates its capability to withstand and recover from malicious attacks. There are two main categories of solutions reported in the literature to achieve this goal. The first category is to design the robust control law to deal with the impacts induced by the attacker's actions, while the other category employs the secure state estimation to compromise the maliciously altered measurements. The overview of recent advances in resilient control of CPS can be found in [43].

On the other hand, the use of sustainable ICT for sustainability is a trend that is on the uplift. With more people realizing the significance of sustainability and taking action, these solutions will only be more widespread and mature.

Technology has evolved with the concept of sustainability. Environmental, social, and governance approaches are frequently tightened with technology, where companies are often seeking solutions in "smart" ways with its help. With the introduction of the Internet of Things (IoT), not only are brilliant applications incubated, but also sustainable solutions that pose significant impacts on society are created.

For instance, resources can be distributed more efficiently and effectively as transportation is armored with information systems. The Internet also enables globalization on the cloud, where transactions can be done without being in person, conserving resources and reducing the carbon footprints created.

The use of ICT in sustainable applications can often be found in two approaches. One of the approaches is the prevention and mitigation of disasters. Figure 6 shows the ICT impact on sustainability with respect to applications, challenges, and outlooks.

- **Zero hunger:** The survey has shown that 88% of agriculture providers are using sensing-related technologies in 2021. Shipping food to places lacking rain or prosperous soil, from planning to management, distribution, and execution, are all enlightened by ICT.
- **Health:** The health industry and tech industry have been working together to provide health services that are more convenient, in time, and affordable. Applications in older adult care such as falling alerts and remote patient monitoring frustrate accidents from occurring. In 2021, US\$250 million have been saved by implementing ICT in healthcare.



FIGURE 6 – ICT on sustainability: applications, challenges, and outlooks.

## The Internet also enables globalization on the cloud, where transactions can be done without being in person, conserving resources and reducing the carbon footprints created.

- *Clean water*: In addition to the preservation of water, people have been using ICT for water quality control and contamination monitoring. Sensors placed in rivers, drainages, and coastlines can collect data efficiently. The data being collected and monitored are pH, resolution of ions, and particles. This is beneficial not only for health aspects, as people can consume high-quality water, but also to the environment, from lands to the creatures living on top of them.
- *Economy growth/industry innovation*: The growth of the economy and industry always surrounds efficiency, which is one of the main characteristics of ICT. As more and more things are interconnected, we are entering the age of Industry 4.0, the age of automation, which critically enhances the efficiency of production. Work in severe environments can be replaced by automation to keep laborers out of danger.

### Synergies of ICT for Future Challenges in Industry

The synergies of all presented ICT research topics are enabling technologies of digital and green transitions through the design, development, deployment, and operation stages to achieve a smart, sustainable, human-centric, and resilient industry.

By applying virtualization technologies in IIoT, modeling the resource usage of services using different HW, designing decision-making and control algorithms, and implementing solutions with low runtime overhead cloud largely reduces the cost of systems while keeping their robustness. Virtualization technologies also provide a foundation for ensuring the robustness of different applications

by separating computing, storage, and network resources. To enable the reconfiguration on the edge level, dynamic resource allocation methods must be further investigated at the virtualization layer.

With frequent changes in requirements, the code needs to be regenerated rapidly. Modifying the code manually is too slow for many current business needs, such as massive customized production or reaction to disturbances. The combined model-driven and data-driven approach can assist code generation processes by maintaining situational awareness of actual operators in the loop. However, how to balance the determinism and intelligence of manufacturing systems between the model-driven and data-driven approaches still needs to be investigated. In addition, the cost of applying large language models for automatic code generation in the industry is still not affordable for most manufacturers. A compact model and budget training method are also required to maximize the benefits of the data-driven approach.

The data-driven code generation requires massive operation data from edge devices. The digital twin can simulate the entire manufacturing process even if the field data are not available. The digital twin can generate output results based on built-in physical processes and can assist in the decision-making of future IIoT systems. With massive data available, how to utilize those data effectively to support process optimization, virtual commissioning, predictive maintenance, and security is yet to be solved for future IIoT systems. Digital twins can assist large distributed control systems during the entire life cycle including the design, development, and testing stages for industries such

as nuclear energy, steel making, and automotive manufacturing. The entire system can be verified before the actual HW installation is completed by applying digital twin models.

In addition to the digital twin, industrial agents could be complemented by AI-based technologies to provide intelligence, decision-making, and cloud and edge computing to accommodate agents running with different real-time constraints and communication infrastructures, particularly IIoT technologies, to support the communication among the distributed control nodes implemented by agents. Data-driven industrial agents could bring intelligent decision-making to the operation stage. For example, when an error occurs on a particular controller during the automotive assembly process, industrial agents deployed to other edge controllers can coordinate with each other to find an alternative plan to maintain normal operation to avoid downtime of the entire system.

Finally, social and environmental issues are not quantified and evaluated. It might be tempting to use data analysis, but data may be a distance from reality. For instance, to measure OICT's impact on learning, is counting the number of children learning online enough, or does the quality of learning also matter? If so, how do we evaluate that? Even if we evaluated a positive progression, how do we measure the relevance of it and OICT? Finally, society is running faster than ever, and the pace of change has become a major concern. Are sustainable solutions able to keep up with the pace of the world? Does OICT have a net positive on sustainability or a net negative one? To answer these questions, benchmarks and indicators that make sense, now and in the future, are necessary to measure the relationship between OICT and sustainability for future industries.

### Acknowledgment

Wenbin Dai is the corresponding author.

### Biographies

**Wenbin Dai** (w.dai@ieee.org) earned his Ph.D. degree from the University

of Auckland, New Zealand, in 2012. He is a full professor at Shanghai Jiao Tong University, Shanghai 200232, China. He is the principal investigator of three NSFC projects and one National R&D Key Program. He currently serves as an associate editor of *IEEE Transactions on Industrial Informatics*, the IEEE Industrial Electronics Society (IES) Technical Committee on Industrial Informatics chair, and an ICT Cluster Delegate. He serves as the working group chair of several IEEE standards in edge computing. He is a Member of IES and a Senior Member of IEEE.

**Paulo Leitão** (pleitao@ipb.pt) earned his Ph.D. degree in electrical and computer engineering from the University of Porto. He is a full professor at Instituto Politecnico de Bragança, Portugal, and coordinator of the Research Centre in Digitalization and Intelligent Robotics, 5300–253 Bragança, Portugal. His research interests are in the field of intelligent and reconfigurable systems, industrial CPSs, multiagent systems, digital twins, and factory automation. He is a member of the Institute of Printed Circuits of several scientific events and served as general cochair of several international conferences. He is a Member of IES and a Senior Member of IEEE.

**Kim Fung Tsang** (ee330015@cityu.edu.hk) earned his Ph.D. degree in electronic engineering from the University of Wales, College of Cardiff, Hong Kong, China. He is an associate professor at the City University of Hong Kong, Hong Kong, China, and also a consultant to the Hong Kong government to promote IoT standard P2668 and develop IoT best practices. He was the founding chair of TC Cloud and Wireless Systems for Industrial Applications (2015–2016). Since 2021, he has been developing the IEEE 1451.5.5 LoRa, IEEE 1451.5.6 SigFox, and IEEE 1451.5.10 NB IoT standards for low-power wide area network smart sensors. He is a Member of IES and a Senior Member of IEEE.

**Yang Shi** (yshi@uvic.ca) earned his Ph.D. degree in electrical and computer engineering from the University

of Alberta, Edmonton, AB, Canada, in 2005. He is currently a professor in the Department of Mechanical Engineering, University of Victoria, BC V8P 5C2, Canada. His current research interests include networked and distributed systems, model predictive control, CPSs, robotics and mechatronics, and autonomous systems. His research has been recognized by many awards including the 2023 CSME Mechatronics Medal. He is a Member of IES and a Fellow of IEEE, ASME, CSME, EIC, and the Canadian Academy of Engineering; he is a registered professional engineer in BC, Canada.

**Gerhard Hancke** (gp.hancke@cityu.edu.hk) earned his B.Eng. and M.Eng. degrees in computer engineering from the University of Pretoria, South Africa, in 2002 and 2003, and a Ph.D. degree in computer science from the University of Cambridge, U.K., in 2009. He is a professor in the Department of Computer Science, City University of Hong Kong, Hong Kong, China. His expertise in industrial ICT links to research interests in reliable communication and distributed sensing for the IIoT. He is a Member of IES and a Fellow of IEEE.

**Lei Shu** (lei.shu@qq.com) earned his Ph.D. degree in computing engineering from the National University of Ireland Galway. He is currently a professor at Nanjing Agricultural University, Nanjing 210037, China, and a Lincoln Professor at the University of Lincoln, LN6 7TS Lincolnshire, U.K. His current research interests include IoT and smart agriculture. He has published more than 500 articles in related conferences, journals, and books in the related areas. His current H-index is 76 in Google Scholar Citations. He is a Member of IES and a Senior Member of IEEE.

**Moris Behnam** (moris.behnam@mdh.se) earned his Ph.D. degree in computer science and engineering from Mälardalen University, Sweden. He is a professor of computer science with a focus on CPSs at Mälardalen University, 721 23 Västerås, Sweden. His research interests include real-time scheduling, distributed embedded real-time systems, industrial cloud

computing, IIoT, and smart automation. He is the director of the innovation and product realization research specialization at Mälardalen University. He has authored/coauthored more than 195 scientific published articles/papers. He is the chair of the IEEE IES Technical Committee on Factory Automation. He is a Member of IES and a Senior Member of IEEE.

**Jan Haase** (janhaase@ieee.org) earned his Ph.D. degree in computer sciences at University Frankfurt/Main, Germany, and his habilitation at Helmut-Schmidt-University, Hamburg, Germany. He is now a full professor at Nordakademie University of Applied Sciences, 25337 Elmshorn, Germany. His main interests are building automation, low-power design methodologies, wireless sensor networks, automatic parallelization, and modern computer architectures. He currently chairs the IEEE Germany Section and is active in IEEE Region 8. Furthermore, he is a member of IEEE Eta Kappa Nu and a voting AdCom member of IES. He is a Member of IES and a Senior Member of IEEE.

**Valeriy Vyatkin** (valeriy.vyatkin@ltu.se) earned his Ph.D. degree in sciences from the State University of Radio Engineering, Taganrog, Russia, his doctor of engineering from Nagoya Institute of Technology, Japan, and his habilitation degree from the Ministry of Science and Technology of Sachsen-Anhalt, Germany. He is on a joint appointment as a chaired professor at Luleå University of Technology, SE-971 87 Lulea, Sweden, and a full professor at Aalto University, FI-00076 Espoo, Finland. His research interests include dependable distributed automation and industrial informatics; software engineering for industrial automation systems; and AI, distributed architectures, and multiagent systems applied in various industry sectors: smart grids, logistics, buildings, data centers, and reconfigurable manufacturing. He is a Member of IES and a Fellow of IEEE.

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