3

The Industry 4.0 Architecture and Cyber-Physical Systems

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3.1 Cyber-Physical Systems (CPSs)

3.1.1 Introduction

Cyber-physical system (CPS) is a transformative technology for managing interconnected systems including both physical assets and computational capabilities (Baheti and Gill, 2011). The greater availability and affordability of sensors, data acquisition systems and computer networks, as well as the competitive nature of today’s industry, means more factories are implementing high-tech methodologies. The ever-growing use of sensors and networked machines has resulted in the continuous generation of high volume data or Big Data (Lee et al., 2013a; Shi et al., 2011). Cyber-physical systems have the potential to handle Big Data and leverage the interconnectivity of machines to reach the goal of intelligent, resilient and self-adaptable machines (Krogh, 2015; National Institute of Standards and Technology, 2013). Furthermore, by integrating CPS into their current production, logistics and service practices, factories could become Industry 4.0 factories, significantly boosting their economic potential (Lee and Lapira, 2013; Lee et al., 2013b). For instance, a joint report by the Fraunhofer Institute and the industry association Bitkom says that with the introduction of Industry 4.0, the German economy will be boosted by 267 billion euros by 2025 (Stadler, 2015). Table 3.1 compares current and Industry 4.0 factories (Lee, 2013).

### Table 3.1
Comparison of Today’s Factory and an Industry 4.0 Factory

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Today’s Factory</th>
<th>Industry 4.0</th>
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</thead>
<tbody>
<tr>
<td>Component</td>
<td>Sensor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Precision</td>
<td>Smart sensors and fault detection</td>
</tr>
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<td></td>
<td></td>
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<tr>
<td>Machine</td>
<td>Controller</td>
<td>Producing &amp; performance</td>
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<tr>
<td>Production system</td>
<td>Networked system</td>
<td>Productivity &amp; overall equipment effectiveness</td>
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Cyber-physical system is in the initial stage of development. For it to reach its full potential in the industry, it is essential to clearly define its structure and methodology. With this in mind, a unified system framework has been designed for general applications. Corresponding algorithms and technologies have been proposed at each system layer to collaborate with the unified structure to achieve enhanced equipment efficiency, reliability and product quality (Lee et al., 2014).

3.1.2 Concept and Characteristics of Cyber-Physical Systems

3.1.2.1 Concept

The term cyber-physical system refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. The ability to interact with and expand the capabilities of the physical world through computation, communication and control is a key enabler of technological development. Opportunities and research challenges include the design and development of next-generation airplanes and space vehicles, hybrid gas-electric vehicles, fully autonomous urban vehicles and prostheses that allow brain signals to control physical objects.

Over the years, systems and control researchers have developed powerful system science and engineering methods and tools, such as time and frequency domain methods, state space analysis, system identification, filtering, prediction, optimization, robust control and stochastic control. At the same time, computer science researchers have made major breakthroughs in new programming languages, real-time computing techniques, visualization methods, compiler designs, embedded systems architectures and systems software, and innovative approaches to ensure computer system reliability, cyber security and fault tolerance. Computer science researchers have also developed a variety of powerful modeling formalisms and verification tools.

Cyber-physical systems research aims to integrate knowledge and engineering principles across the computational and engineering disciplines (networking, control, software, human interaction, learning theory, as well as electrical, mechanical, chemical, biomedical, material science and other engineering disciplines) to develop new CPS science and supporting technology.

In industrial practice, many engineering systems have been designed by decoupling the control system design from the hardware or software implementation details. After the control system is designed and verified by extensive simulation, \textit{ad hoc} tuning methods have been used to address modeling uncertainty and random disturbances. However, the integration of various subsystems, while keeping the system functional and operational, has been time-consuming and costly. For example, in the automotive industry, a vehicle control system relies on system components manufactured by different vendors with their own software and hardware. A major challenge for original equipment manufacturers who provide parts to a supply chain is to hold down costs by developing components that can be integrated into different vehicles (Baheti and Gill, 2011).

The increasing complexity of components and the use of more advanced technologies for sensors and actuators, wireless communication and multicore processors pose a major challenge for building next-generation vehicle control systems. Both the supplier and integrator need new systems science that enables reliable and cost-effective integration of independently developed system components. In addition, both theory and tools are needed to develop cost-effective methods to (Baheti and Gill, 2011):

1. Design, analyze, and verify components at various levels of abstraction, including the system and software architecture levels, subject to constraints from other levels;
2. Analyze and understand interactions between the vehicle control systems and other subsystems (engine, transmission, steering, wheel, brake and suspension);
3. Ensure safety, stability, and performance while minimizing vehicle cost to the consumer. New functionality and the cost of vehicle control systems are increasingly becoming major differentiating factors in the business viability of automobile manufacturing.

Cyber-physical systems is an emerging research area that involves the overlapping and integration of multiple fields of science and engineering; computer scientists and network professionals must collaborate closely with experts in many different fields such as automation and control, civil engineering,
mechanical engineering and biology. Therefore, definitions of CPS mostly reflect the perspective of the scholars positing them (Liu et al., 2017).

Lee defines CPS as the integration of computational and physical processes, with embedded computer and networks monitoring and controlling the physical processes. Physical processes affect computations by feedback loops and vice versa (Lee, 2007). In another study, He regards CPS as controllable, credible and scalable networked physical equipment systems, an in-depth integration of computation, communications and control ability on the basis of environmental perception (He, 2010). Finally, Liu et al. (2017) say that through the feedback loop of mutual effects between computing processes and physical processes, in-depth integrations and real-time interactions increase or expand the function of networks and physical systems and monitor or control a physical entity in a safe, reliable, efficient and real-time way.

The service-oriented architecture of CPS is shown in Figure 3.1.

Gonzalez et al. (2008) propose that CPS is a network physical engineering system, which monitors and controls the operations of physical system through computation. The US Defense Advanced Research Projects Agency says the physical network system refers to systems whose functions are largely derived from software and electromechanical systems. In fact, all defense systems (such as aircraft, spacecraft, naval vessels, ground vehicles, etc.) and their subsystems are CPS. Integrated circuits, microelectromechanical systems and nanoelectromechanical systems are also types of CPS (Liu et al., 2017).

Wireless sensor networks (WSNs) and the Internet of Things (IoT) are different. Wireless sensor network senses a signal but does not necessarily identify a specific object out of many objects being sensed. It emphasizes the perception of information and provides data support for a variety of specific applications through data collection, processing, integration and routing.

IoT interconnects Internet information sensing devices such as wireless sensors and radio-frequency identification (RFID) through wireless networks and Internet technology; it is a new type of network that can realize the overall perception, reliable transmission and intelligent processing of information. In contrast, CPS is a controllable, credible and scalable network system; it integrates computing, communication and control on the basis of information acquisition in IoT. Through the feedback loop of the interaction between the calculation process and the physical process, deep integration and real-time interactions are realized to increase or to extend a new function, so that a physical entity can be detected or controlled in a safe, reliable, and efficient way. The IoT generally has a perception, but no or just simple control of the physical world, while CPS not only has the ability to sense the physical world, but also possesses the ability to control. Its requirement of computing capability for equipment far exceeds that of IoT and WSN (Liu et al., 2017).

To sum up, CPS features a tight combination of and coordination between network systems and physical systems. By organic integration and in-depth collaboration of computation, communications and control (3C) technology, CPS can realize the real-time sensing, dynamic control and information

![FIGURE 3.1 Service-oriented architecture of CPS. (From Liu, Y. et al., IEEE/CAA J. Autom. Sinica, 4, 27–40, 2017.)](image-url)
services of large engineering systems. The term CPS also refers to distributed heterogeneous systems that contain network systems and physical systems with different functions; in addition, the structure and function vary among their subsystems and are distributed in different geographic scopes. Wired or wireless communications are needed for subsystems to coordinate. Cyber-physical system integration is shown in Figure 3.2.

3.1.2.2 Characteristics

Cyber-physical system interacts with physical systems through networks; the end system of a CPS is normally a centralized and tightly coupled embedded computing system, which contains a large number of physical systems composed of intelligent wireless sensors (Liu et al., 2017). CPS has the following characteristics:

1. Physical system: This includes physical system design such as hardware design, energy management, hardware size and connectivity encapsulation and system testing. Engineers and scientists in this field have a deep understanding of mechanics, electronics, biology and chemistry; they understand the technical characteristics of sensors, and they know how to process measurement data using signal processing technology. Every physical system has its own network characteristics, a maximized multilevel network coverage, a variety of complex temporal and spatial scales to meet the time requirements of different tasks and a high degree of automation.

2. Information system: The information in physical system engineering can be transformed into the rules and models of a software system. The most basic task is to reach a balance among factors such as real-time system, network system, file system, hierarchical storage system, memory management, modular software design, concurrent design and formal verification.

3. Integration of heterogeneous systems: CPS are heterogeneous distributed systems featuring the integration and interaction of information systems and physical systems.

4. Security, real-time capability and predictability: Because network systems and physical systems are open, invasions, tampering, counterfeiting and other malicious attacks may occur, as well as delays in network transmission. Cyber-physical system must be able to offer credibility, security, validity, real-time capability, dynamism and predictability. For credibility, the identity of information-collecting sources or control instruction senders must be authenticated, and the receiver must be able to determine the real identity of the sender to prevent counterfeiting. Security requires the encryption and decryption of sent or received information, and the privacy of information must be protected. For validity, the accuracy of processing, as well as the
validity and integrity of information or instructions sent, must be guaranteed to prevent uncertainties and noise in CPS processing from affecting the system’s processing accuracy. Real-time capability means collected information or instructions must be transmitted in a timely manner to meet the real-time requirements of task processing. Dynamism includes dynamic reorganization and reconfiguration, automatically adjusting rules and generating commands based on the task requirements; it also includes changes in external environments to eliminate bias and meet task requirements according to preset rules. With predictability, CPS resource allocation strategy can reasonably allocate resources to multiple competing real-time tasks at any moment and in any case, so that the real-time requirements of every real-time task can be satisfied.

3.1.3 Research on CPS Architecture

Cyber-physical system research has just begun. As CPS is the integration of multidisciplinary heterogeneous systems, without a unified global model, CPS research is carried out by experts in various areas from the perspective of applications in their own field. At present, CPS research mainly focuses on system architecture, information processing and software design.

Modeling can be considered as the technology to describe a target system before completion. Cyber-physical system architecture is being researched and developed, and CPS models must be modified and integrated on the basis of existing physical systems, network systems and computer system structure. Abstraction and modeling of communication, computation and physical dynamics on different scales including time scales are also needed to develop CPS.

The CPS system structure can be divided into three layers: user, information system and physical system layers. The physical system is the foundation of the CPS; it is composed of embedded systems, sensor networks, smart chips and so on, and it takes charge of the collection and transmission of information and the execution of control signals. The information system layer is mainly responsible for the transmission and processing of the data collected by the physical system. The user layer completes the work, including data query, strategy and safety protection, in a human–computer interaction environment. Cyber-physical system runs as a closed loop. The architecture of CPS is shown in Figure 3.3 (Liu et al., 2017).

The function of each part of the architecture (Figure 3.3) is explained as follows:

1. Sensor networks: Acquire real-time data through a variety of sensors and embedded systems; conduct analog-to-digital conversion of collected data and other processes, including data encryption and data integration through collection nodes; protect the security of data transmission (privacy, integrity and non-repudiation); reduce the network energy consumption by energy management; apply real-time data protection technology to real-time processing.

2. Next-generation network systems: Deploy anti-hacking and defense technology against a variety of network attacks; ensure the safety of data transmission with high-performance encryption algorithms and certification authority (CA) authentication technology; realize rapid exchange of data transmission by optimizing existing routing algorithms; change the existing network system structure through “best efforts” to provide real-time network transmission services.

3. Data center: Stores data transmitted by sensor networks through next-generation network systems; checks authenticity and integrity of received data and stores data if they pass inspection, otherwise sends a message to control center (control center then sends control signals to the actuator who notifies the sensor network nodes to collect data again); conducts routine maintenance of the database; responds to instructions sent by control center, such as query; performs regular emergency treatments to prevent database from collapse.
4. Control center: Receives inquiry instructions sent by users; sends query command to data center after identity authentication; categorizes the query results according to control strategies; reports back to the user if queries meet the requirements, otherwise determines the location of the node by node positioning technology and sends control instructions to actuators for corresponding processing; conducts forecast analysis and performance analysis of CPS behavior through data mining technology and uncertainty processing technology; detects network and node failure through fault diagnosis technology and conduct corresponding processing; ensures the real-time control processing of CPS through real-time control technology. It should be noted that control center configuration policy can be dynamically adjusted according to users’ needs.

5. Actuator networks: Receive control instructions from control center; send control instructions to corresponding nodes.

6. System user: Communicates with CPS; sends inquiry instructions to control center; receives feedback data; can send definitions and revised control strategies to control center to be executed. System users include a variety of WEB servers, individual hosts and external devices.

In this model, CPS runs under closed-loop control; the model considers real-time capability, security and system performance so that it can preliminarily meet future CPS requirements.

Some scholars have studied the system architecture of CPS from different application perspectives (Liu et al., 2017). For example, Sun et al. (2007) argue that the advanced power grid is a complex real-time system with network and physical components. Each part may function well independently, but not when they are combined, because the interference may cause errors, for example, the violation of Nyquist rate in the frequency domain. They propose using RT-Promela to build a model that can represent frequency interference and use the real-time interference of real-time sensor protocol for information via negotiation detection to test the accuracy of CPS components. The model solves the problem of multiple clock variables in collaboration processing caused by a lack of real-time and asynchronous interaction of components (Sun et al., 2007).

Ilic et al. (2010) established a CPS energy system dynamic model with distributed sensing and control and discussed the process of information exchange between components in this model; they also discussed using the model to develop interactive protocols between an embedded system control terminal and a network system (Ilic et al., 2010). In another study, He built a coordination framework based on the perception of model and future energy system control. He also improved the operation of complex power system using data mining techniques and new sensor technologies (He, 2010). Unfortunately, these studies can only be applied in power systems and do not have enough versatility (Liu et al., 2017).

An actuator network is composed of a plurality of actuator units and control nodes. Control nodes are responsible for receiving the control command from the control center and sending commands to one or more specific actuator unit for execution, so that certain physical attributes of the physical world can be adjusted and controlled. To solve the problem of the collaborative design of feedback control and scheduling, Zhang et al. discuss a method of scheduling when several actuators are controlled by a controller (single processor) to achieve a balance between the time delay and the control performance by adopting off-line and online strategies, respectively. However, the method only considers the physical system, i.e., the control part, and ignores the information system (Zhang et al., 2008a). Tan et al. (2010) study the architecture of CPS and propose a CPS system model adopting an event-driven real-time scheduling scheme, which solves the problem of real-time task scheduling in the sensor nodes periodic task model and the actuator event-triggered task model. However, the authors do not provide experimental verification; thus, the system running efficiency is not verified (Tan et al., 2010). Zhang et al. (2008b) propose to simultaneously process periodic and non-periodic events in CPS-oriented real-time middleware, and they suggest the corresponding algorithms of access control and load balancing, but they do not analyze the time cost of middleware services. Finally, the random server concept proposed by Faggioli et al. (2010) performs...
well in processing event-triggered random tasks and meets time predictability requirements, but there are deficiencies in the processing mechanism if there is time overhead or server overload (Liu et al., 2017).

Cyber-physical system has strict requirements for real-time capability and the abstraction of physical awareness. As system components might need synchronous or asynchronous interaction with the physical world, a global reference time is fundamental for all CPS components to communicate and work properly.

Information and events of physical systems are abstractions of system components, and the objects abstracted have a life cycle. Different system components can have different credibility and reliability for different input sources according to individual preferences, experiences and knowledge. Thus, the abstraction of the same input events may produce completely different outputs because of the different system components. Therefore, CPS must have unified time, trust quantification and communication mechanisms at the system level.

Tan puts forward a CPS architectural prototype using aspects of the global reference time, information-driven events, trust quantification, publish or subscribe plans, control semantics and network technology. In this architectural prototype, an advanced control unit adopts a tight coupling sensor and actuator mechanism and conducts precise real-time control at the system level to ensure the validity of the control loop (Tan et al., 2008). However, the prototype does not solve problems such as how to publish a scheduling plan or how to define event models and information models in large-scale heterogeneous CPS. Crenshaw et al. (2007) design plants controlled by external association, executive control equipment and domain models to estimate the state of plants; they create a simple reference model that satisfies security requirements.

In CPS, it is difficult to realize real-time predictability to control physical systems. To enhance the sustainability and predictability of CPS, Lin and Panahi (2010) study real-time service-oriented architecture (SOA) and establish a real-time service-oriented architecture enterprise service bus model. They use real-time SOA middleware services to establish a service accountability mechanism and a real-time global resource management service process (Lin and Panahi, 2010). Because of the limitations of services and known resources, the authors adopt the method of reserving resources and using middleware to monitor the performance of every service in the process in advance to ensure real-time prediction. Pasqualetti et al. (2013) propose a model and method of automatically extracting cyber-physical systems using a custom programming language; it can be applied to temperature sensors with fault tolerance. However, the model lacks versatility because the abstraction accuracy of the automatic processing is not considered, and the scope of application is limited (Liu et al., 2017).

Cyber-physical system research is limited by the specific application environment, the development environment and the theoretical system in question. Most existing system models were established specifically for different local applications and do not consider the correlation of various demands and restrictions in CPS networks. As there is no mature global system model, further research is necessary (Liu et al., 2017).

### 3.2 CPS 5C Level Architecture

The so-called 5-level CPS structure, or the 5C architecture, provides step-by-step guidelines for developing and deploying a CPS for manufacturing applications. In general, CPS has two main functional components:

1. Advanced connectivity ensures real-time data acquisition from the physical world and information feedback from cyberspace;
2. Intelligent data management, analytics and computational capability construct cyberspace.

However, these requirements are abstract and not specific enough for implementation. In contrast, the 5C architecture clearly defines, in a sequential workflow manner, how to construct CPS from the initial data acquisition, to the analytics, to the final value creation. Figure 3.4 outlines the 5C architecture.
3.2.1 Smart Connection

Acquiring accurate and reliable data from machines and their components is the first step in developing a CPS application. The data might be directly measured by sensors or obtained from controllers or enterprise manufacturing systems, such as enterprise resource planning (ERP), manufacturing execution system (MES), supply chain management (SCM) and collaborative manufacturing management (CMM). Two important factors at this level must be considered. First, considering various types of data, a seamless and tether-free method to manage data acquisition procedure and transferring data to the central server is required where specific protocols such as MTConnect are useful (Vijayaraghavan et al., 2008). Second, proper sensors (type and specification) must be selected for the first level (Lee et al., 2014).

3.2.2 Data-to-Information Conversion

Meaningful information must be derived from the data. Several tools and methodologies have been developed to convert data to information, with algorithms designed specifically for prognostics and asset health management applications. By calculating health, the remaining useful life (RUL) and so on, the second level of CPS architecture brings self-awareness to machines (see Figure 3.5) (Lee et al., 2014).

3.2.3 Cyber

The cyber level is a central information hub, with information pushed to it from every connected machine. Massive amounts of information are gathered; thus, specific analytics have to be used to extract relevant information on the status of individual machines. With these analytics, the performance of a single machine can be compared with others in the fleet and rated accordingly. In addition, similarities between machine performance and the performance of previous assets (historical information) can be measured to predict future behavior (Lee et al., 2014).
3.2.4 Cognition

Implementing CPS on this level generates a thorough knowledge of the monitored system. Proper presentation of the acquired knowledge to expert users will lead to the correct decision. As comparative information and individual machine status are both available, it is possible to determine the priority of tasks and optimize the maintenance process. Proper info-graphics are necessary to completely transfer acquired knowledge to users (Lee et al., 2014).

3.2.5 Configuration

The configuration level features feedback from cyberspace to physical space. This level acts as a supervisory control system or a resilience control system. The machines self-configure and self-adapt, and the corrective and preventive decisions made in the cognition level are applied to the monitored system (Lee et al., 2014).

3.3 Implementation of 5C CPS Architecture in Factories

Implementing CPS in today’s factories has advantages for components, machines and production systems (see Table 3.1).

At the component stage, once the sensory data from critical components are converted into information, a cyber-twin of each component becomes responsible for capturing time machine records and synthesizing future steps to provide self-awareness and self-prediction. At the machine stage, more advanced machine data, e.g., controller parameters, are aggregated to the components’ information to monitor the status and generate the cyber-twin of each particular machine. These machine twins in CPS provide additional self-comparison capability. At the production system stage, the aggregated knowledge from components and machine level information provide self-configurability and self-maintainability to the factory. This level of knowledge guarantees a worry-free and near-zero downtime production and provides optimized production planning and inventory management plans (see Figure 3.6) (Lee et al., 2014).
3.3.1 CPS-Based Smart Machines

Cyber-physical system-based smart machines are becoming more popular and more viable in the industry. In this section, we explain how one industrial process, machining, can benefit from the application of CPS.

Machining processes in the manufacturing industry represent a highly dynamic and complex situation for condition-based maintenance and prognosis and health management (PHM). A computer numerically controlled (CNC) machine can usually handle a wide range of materials with different hardness and geometric shapes and consequently requires different combinations of machine tool and cutting parameters to operate. Traditional PHM strategies are usually developed for a limited range of machine types and working conditions and cannot handle an entire manufacturing floor where machines can be utilized under a wide range of working regimes that cannot be modeled comprehensively beforehand. A CPS framework with a 5C structure is a better solution. A CPS for machine tools can be used to process and analyze machining data and to evaluate the health condition of critical components (e.g., tool cutter), improving the overall equipment efficiency and reliability by predicting upcoming failures, scheduling maintenance beforehand and controlling processes adaptively.

In factories, machining processes start with sawing large pieces of material into designated sizes. Given the upstream nature of the sawing process, the quality and speed of sawing affect the entire production, and any error could be propagated to the following steps and result in bad quality products. Performing accurate cuts requires a slower cutting process, and this hampers the overall productivity of the manufacturing line. Therefore, while it is not possible to maximize these two requirements at the same time, an optimal balance between surface quality and speed has to be achieved. In such situations, the health status of the band sawing machine and its components play a significant role in both the speed and quality of cuts. The availability of precise health information from the machine will help determine the optimum cutting speed and accuracy.

As shown in Figure 3.7, at the connectivity level, data are acquired from machines through both add-on sensors and controller signals. In addition to the add-on vibration, acoustic emission, temperature and sensor information, 20 control variables, such as blade speed, cutting time and blade height, are taken from the programmable logic controller (PLC) to clarify the working status of each machine. The data are now processed in the industrial computer connected to each machine.
At the conversion level, the industrial computer performs feature extraction and data preparation. The feature extraction consists of extracting conventional time domain and frequency domain features, such as RMS, kurtosis, frequency band energy percentage and so on, from vibration and acoustic signals. Calculated features, along with other machine state data, are sent through Ethernet or a Wi-Fi network to the cloud server where the feature values are managed and stored in the database (Lee et al., 2015).

At the cyber level, the cloud server applies an adaptive clustering method to segment the blade performance history (from installation to the present time) into discrete working regimes based on the relative change of the features compared to the normal baseline and the local noise distribution (see Figure 3.8). The adaptive clustering method compares the current values of the features with the baseline and historical working values. It identifies the most suitable cluster from the history to match with the present working condition. If no suitable cluster is found, the algorithm generates a new cluster as a new working regime and generates related health models for that regime. If the same working condition happens again, the algorithm has its signatures in memory and will automatically cluster the new data into that specific working regime (Yang et al., 2015).

The health stages can be further utilized at the cognition level and configuration level for optimization purposes. For example, when the blade is new, a higher cutting speed can be used for high productivity without hampering the quality, while after a certain amount of degradation has been detected, a more moderate cutting should be applied to ensure quality. To help in the decision-making process, Web and iOS-based user interfaces have been developed so that the health information of each connected machine tool can be accessed in real time (see Figure 3.9) (Lee et al., 2015).

Cyber-physical systems are becoming more common in the manufacturing industry. Managing industrial big data is challenging, making a generic architecture for implementing CPS necessary. The 5C architecture discussed here can automate and centralize data processing, health assessment and prognostics. This architecture covers all necessary steps from acquiring data, processing the information, presenting information to the users and supporting decision-making. The health information generated...
by the system can also be used for higher level functions, such as maintenance scheduling and optimized control, to achieve higher overall system productivity and reliability. As the case study suggests, the 5C architecture would be helpful in processing and managing a fleet of CNC sawing machines. Its application would be equally useful in other sectors. Integration of the 5C CPS architecture is still in its infancy, but all five levels of the architecture offer an enormous possibility. For example, the cyber level has the potential to develop new algorithms for fleet-level analysis of machines’ performance over distributed data management systems (Lee et al., 2015).
3.4 Adaptive Clustering for Self-Aware Machine Analytics

The effectiveness of the proposed CPS structure relies on the performance of the data analysis functions deployed at the cyber level. The cyber level serves as a bridge connecting the lower level data acquisition and upper-level cognition functions; it is required to autonomously summarize, learn and accumulate system knowledge based on data collected from a group of machines. The system knowledge includes possible working regimes, machine condition, failure modes and degradation patterns; these, in turn, are used by cognition and reconfiguration functions for optimization and failure avoidance.

Because of complications in machine configuration and usage patterns, autonomous data processing and machine learning are of high priority, especially as the traditional *ad hoc* algorithm model cannot be applied to complex or even unexpected situations. A two-step autonomous machine learning and knowledge extraction methodology has been proposed to perform health assessment and prognostics within the CPS structure.

3.4.1 Similarity-Based Clustering for Machine Condition and Working Regimes

In a fleet, there is always a certain amount of similarity among machines. For example, machines performing similar tasks or having similar service times may have similar performance and health condition. Based on such similarities, machine clusters can be built as a knowledge base representing the performance and working condition of different machines (Bagheri et al., 2015).

Unsupervised learning algorithms such as self-organizing map (SOM) and Gaussian Mixture Model can be used to autonomously create clusters for different working regimes and machine conditions. The adaptive clustering methodology proposed in Figure 3.10 utilizes an online update mechanism: the

![FIGURE 3.10 Adaptive clustering algorithm. (From Bagheri, B. et al., Cyber-physical systems architecture for self-aware machines in industry 4.0 environment, Center for Intelligent Maintenance Systems, University of Cincinnati Cincinnati, OH, 1622–1627, 2015.)](image-url)
algorithm compares the latest input to the existing cluster and tries to identify one cluster that is most similar to the input sample using a multidimensional distance measurement.

The search for a similar cluster will have one of two possible results (Bagheri et al., 2015):

1. Similar cluster found. If it is this case, the machine from which the sample has been collected will be labeled as having the health condition defined by the identified cluster. Depending on the deviation between the existing cluster and the latest sample, the algorithm will update the existing cluster using new information from the latest sample.

2. No similar cluster found. In this case, the algorithm will hold its operation with the current sample until it sees enough out-of-cluster samples. When the out-of-cluster samples exceed a certain number, it means there is a new machine behavior that has not been modeled. The algorithm will automatically create one or more new clusters to represent the new behavior. The clustering algorithm can be very adaptive to new conditions. Moreover, the self-growing cluster can be used as the knowledge base for health assessment in the proposed cyberspace. With such a mechanism, different machine performance behavior can be accumulated in the knowledge base and utilized in future health assessments.

### 3.4.2 Prognostics of Machine Health under Complex and Multi-regime Conditions

After the health condition and the working regimes are identified for each machine, the next step is to predict the RUL. First, the relationship between machine degradation and the utilization (stress) history is built using utilization history and measurement data. Many existing prediction algorithms fail to perform well for in-field machines because they cannot handle complex working regimes and may alter the actual degradation pattern from lab tests. The proposed prediction method is based on the fact that degradation is caused by more than just time. Other parameters such as stress participate in machine degradation. Therefore, a general-purpose prediction algorithm has to be based on stress vs. life relationship. The workflow of the proposed methodology is presented in Figure 3.11.

Steps 1 and 2 extract and accumulate stress vs. life information and use this as the knowledge foundation for prognostics. Steps 3 and 4 use the knowledge base to make predictions about a particular machine. A stress matrix is used to determine stress; it summarizes the major stress factors that cause a particular system to degrade. A sample stress matrix for rotating machinery is presented in Table 3.1.

**FIGURE 3.11** Utilization matrix-based prognostics. (From Bagheri, B. et al., Cyber-physical systems architecture for self-aware machines in industry 4.0 environment, Center for Intelligent Maintenance Systems, University of Cincinnati Cincinnati, OH, 1622–1627, 2015.)
TABLE 3.2
Stress Matrix for Rotating Machinery

<table>
<thead>
<tr>
<th></th>
<th>High Load</th>
<th>Low Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>High speed</td>
<td>Degradation rate 1</td>
<td>Degradation rate 1</td>
</tr>
<tr>
<td>Low speed</td>
<td>Degradation rate 1</td>
<td>Degradation rate 1</td>
</tr>
</tbody>
</table>

*Source:* Bagheri, B. et al., Cyber-physical systems architecture for self-aware machines in industry 4.0 environment, Center for Intelligent Maintenance Systems, University of Cincinnati Cincinnati, OH, 1622–1627, 2015.

For some systems, such as CNC machines, more dimensions (e.g., material hardness, machining parameters, volume of removed material, etc.) need to be added to the stress matrix to cover all major factors that cause degradation. After the stress matrix is defined, machine learning algorithms such as Bayesian belief network and hidden Markov model can be used to relate the different degradation rates observed in a fleet of equipment to the corresponding stress history. Eventually, a degradation rate as shown in Table 3.2 can be generated and used for prediction under different usage patterns in real-world applications (Bagheri et al., 2015).

3.5 Classic Applications of CPS

Computation technology has been expanded to include all human existence and activities, both cyber and physical worlds, to realize the integration and unity of the physical world and information systems.

The rapid development of the Internet is allowing us to interconnect a variety of devices so that we may process information rapidly and efficiently. For example, IoT permits the interconnection and information exchange of all kinds of items through the sensing equipment attached to them by techniques such as RFID and 802.15.4; the original people–people interaction on Internet is transformed into a wider content connection network. Like IoT, CPS combines computational space and the physical world; it also has the function of control in addition to basic perception functions (Liu et al., 2017).

Cyber-physical system has an extensive range of applications, including aerospace equipment, medical devices and systems, manufacturing, traffic control, environmental control, critical infrastructure (electricity, irrigation networks, communication systems), industrial production data collection automation, automated processes, energy consumption and regeneration, the next generation power grid, future defense systems, distributed robotics, civil infrastructure and so on. With the continuous development and improvement of science and engineering, CPS will expand into areas such as interventions (collision avoidance), precision (robotic surgery and nanoscale manufacturing), data mining (data classification, evaluation, predicted aggregation, etc.), dangerous or inaccessible operating environments (search and rescue, firefighting and deep-sea exploration), coordination (air traffic control, war) and efficiency (zero net energy buildings) (Wolf, 2009).

Tan et al. (2009) give three examples of classic applications of CPS: health care and medicine, intelligent roads and unmanned vehicle and electric power grid (Rajkumar, 2007; Krogh 2015).

A. Health care and medicine

The domain of health care and medicine includes national health information, electronic patient records, home care information, hospital operating rooms and so on. These are increasingly controlled by computer systems with hardware and software components; they represent real-time systems with safety and timing requirements. An operating room CPS is shown in Figure 3.12 (Shi et al., 2011).

B. Electric power grid

In power grids, electronics and embedded control software form a CPS; the design is influenced by fault tolerance, security, decentralized control, and economic or ethical social aspects (McMillin et al., 2007). Figure 3.13 shows an electric power grid CPS (Rajkumar, 2007; Krogh, 2015).

C. Integrated intelligent roads with unmanned vehicles
With the development of sensor networks, embedded systems and so on, CPS has the potential to create integrated intelligent roads with unmanned vehicle, as shown in Figure 3.14 (Shi et al., 2011).

3.6 Classification of CPS in Context of Industry 4.0

The basic aim of Industry 4.0 is to ensure global competitiveness by adapting manufacturing units to meet changing customer requirements within the shortest possible time. This adaptation integrates all upstream and downstream stages of production, and only products that are definitely needed are produced. The optimal integration of people with their particular skills makes the adaptation possible.

One approach to the need for individualization and flexibilization involves networking machines, equipment, tools, storage systems and emerging products in the IoT; a factory networked in such a way is termed a “smart factory.”

However, how can objects be networked? All nonhuman participants in manufacturing exist in the real world of production that can be grasped with the five senses, but they also exist beyond that in a “virtual image” that reflects the real world and is supplemented by information. This virtual image can be found in the world of information technology (IT) and depict all the possibilities and abilities of the production participants as well as their current states.

Based on the information of the virtual image, it is possible for an individual decentralized participant in manufacturing to make independent decisions and to communicate these directly to neighboring production participants. For example, an intelligent transport container may request supplies from another machine if it discovers that the relevant bin is empty.
Every participant in production has a virtual image and can be networked to interact with other production participants; this is the CPS we have been discussing in the previous sections. “Cyber” refers to the virtual image, and “physical” refers to the object that can be perceived.

As shown in Figure 3.15, CPS interact among each other; information is provided, and high-level recipients and decision-makers, from local machine operators to external customers and suppliers, are integrated. For example, a tool itself may notice the first signs of wear and tear and order its own replacement from external tool suppliers (Amberg, 2015).

3.6.1 Building Blocks of Industry 4.0: Cyber-Physical Systems

Cyber-physical systems are building blocks in Industry 4.0 and part of the Industry 4.0 vision.

They are combinations of intelligent physical components, objects and systems with embedded computing and storage possibilities; these are connected through networks and are the enablers of the smart factory concept of Industry 4.0 in the IoT. Simply put, CPS refer to the bridging of digital (cyber) and physical in an industrial context (i-SCOOP (a)).

3.6.2 Cyber-Physical Systems (CPS) in Industry 4.0 Vision

Cyber-physical systems in the Industry 4.0 vision are based on the latest control systems, embedded software systems and an IP address. In the Industry 4.0 context of mechanics, engineering and so on, CPS are the next stage in an ongoing integration of functions. More specifically, the ongoing improvement-driving Industry 4.0 started with mechanical systems, moved to mechatronics (e.g., controllers, sensors, actuators) and adaptronics (i.e., active and adaptive mechanical systems) and is now entering the CPS stage (see Figure 3.16a and b) (i-SCOOP (a)).

Cyber-physical system essentially enables us to make industrial systems able to communicate and network, adding to existing manufacturing possibilities. New possibilities are emerging in areas such as structural health monitoring, track and trace, remote diagnosis, remote services, remote control, condition monitoring, systems health monitoring and so forth. With networked and communicating cyber-physical modules and systems, connected or smart factories, smart health, smart cities, smart logistics and so on have become a real possibility (i-SCOOP).
It is noted that there is a difference between CPS and cyber-physical manufacturing systems or cyber-physical production systems (CPSS), as the latter two are more technological and have a less important process and application dimension (i-SOCOOP (a)).

3.6.3 Cyber-Physical Systems: Summary of Key Characteristics

In 2010, Professor Edward A. Lee from the University of California, Berkeley, defined CPS as follows: “Cyber-Physical Systems (CPS) are integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.” On his page on the Berkeley website, Lee shows the CPS concept in the form of a mind map (see https://www2.eecs.berkeley.edu/Faculty/Homepages/lee.html).
To sum up, the key characteristics of CPS are the following (i-SCOOP (a)):

- CPS represent an evolution in manufacturing, mechanics and engineering. The essential dimensions are the bridging of digital and physical worlds, made possible by Internet technology and the bridging or convergence of IT and operational technology (OT).
- CPS can communicate. They have intelligent control systems, embedded software and communication capabilities and can be connected in a network of other cyber-physical systems.
- CPS can be uniquely identified. They have an IP (Internet protocol) address; they use Internet technology and are part of an Internet of Everything in which they can be uniquely addressed (each system has an identifier).
- CPS have controllers, sensors and actuators. Although this was already the case before CPS (see earlier discussion of mechatronics and adaptronics), the IoT increases their importance.
- CPS are the basic building blocks of Industry 4.0 and the enablers of additional capabilities in manufacturing (and beyond) such as track and trace and remote control.
- CPS enable smart factories, smart logistics (Logistics 4.0) and other smart areas of applications, among others.
- CPS include simulation and twin models, smart analytics and self-awareness (self-configuration).

3.7 Operational Technology and Information Technology

3.7.1 OT Support

The term has only recently come into relatively widespread use and does not have an agreed-upon definition. Gartner refers to OT as “hardware and software that detect or cause a change through the direct monitoring and/or control of physical devices, processes and events in the enterprise” (Gartner, 2011). This seems to have come from an effort to understand OT from an IT point of view.

Many OT systems often depend on the same server, network and operating system technology as IT systems, leading some to consider that IT and OT are on converging trajectories. However, the drivers of the systems’ designs tend to be prioritized differently. Simply stated, OT is the application of computers to monitor and/or control some aspect of the physical world. Put otherwise, OT systems have additional attributes allowing them to control or monitor physical processes. Thus, their design parameters are often very different from IT systems.

Examples of OT systems include supervisory control and data acquisition (SCADA) systems used by grid companies and building management systems used in the facilities management industry. Other examples include robots, CCTV, energy management and fire alarm systems. These require a network and server architecture that enables interoperability, provides resilience and offers security.

Cost pressures have led to progressive technology convergence, and an increase in the number of OT systems and devices developed using commercial off-the-shelf operating systems and network protocols. The requirement for increased uptime has led to the demand for 24/7 support, often fulfilled via some form of remote access.

3.7.2 IT Support

Software tools are crucial to operating the Industry 4.0 smart factory. Figure 3.17 depicts the well-known pyramid structure of modern production systems (Rojko, 2017), each with its own software support.

The ERP tool is implemented on the business level, at the top of the pyramid. Enterprise resource planning supports enterprise-wide planning such as business planning, SCM, sales and distribution, accounting, human resource management and so on. Usually, commercially available solutions are implemented. A leading solution is Systems, Applications and Products in data processing (SAP), developed by the German company SAP SE. Most available ERP solutions do not support fast adaptation in production planning when unplanned events occur (Rojko, 2017).
An MES is used on the second level of the pyramid. These software applications support production reporting, scheduling, dispatching, product tracking, maintenance operations, performance analysis, workforce tracking, resource allocation and so on. Manufacturing execution system covers aspects such as management of the shop floor and communication with the enterprise (business) systems. Most of the software solutions available on the market are centralized and not distributed to the shop floor. This is a major limiting factor when flexibility is needed because of the dynamics of customers’ orders and/or the changing production environment, including shop floor configuration.

The next operative level is the process level control; here SCADA control system software is common.

The bottom level of the pyramid is the machine or device level. Unlike the top two layers, this level has a naturally distributed control level (Rojko, 2017). Software includes PLCs, robot controllers and other controllers.

Enterprise resource planning and MES tools represent basic software in the company and have been used for many years. They typically have a modular structure and are centralized in their operation; thus, they have limited capability for dynamic adaptation of the production plan (Bratukhin and Sauter, 2011). Nevertheless, already implemented conventional ERP and MES systems should not be seen as obstacles to the introduction of the Industry 4.0 concept. In fact, the introduction of a common MES tool requires an advanced IT infrastructure on the shop floor level, and this is a precondition for further development toward smart factory (Rojko, 2017).

The next important issue is the integration of information available in ERP, MES and other software tools used in the company, such as customer–relationship management or business intelligence. Problems such as database integration and communication protocols still need to be resolved (Bratukhin and Sauter, 2011).

In short, for Industry 4.0, the classic pyramid structure is not flexible enough to adapt to dynamic changes. A distributed MES solution, where most of the functions are decentralized, may be more suitable for reconfigurable production systems (see Figure 3.18). For full support of reconfigurable systems, however, a continuous flow of information (vertical and horizontal integration) between all elements must be realized (Rojko, 2017).
3.8 IT and OT Convergence in Industrial IoT

Information technology or operational technology convergence is the integration of IT systems used for data-centric computing with OT systems used to monitor events, processes and devices and make adjustments in enterprise and industrial operations.

Information technology includes any use of computers, storage, networking devices and other physical devices, infrastructure and processes to create, process, store, secure and exchange all forms of electronic data. Operational technology, traditionally associated with manufacturing and industrial environments, includes ICS such as SCADA.

While IT covers communications as a part of its information scope, OT has not traditionally been a networked technology. Many devices for monitoring or adjustment were not computerized, and those with computing resources generally used closed, proprietary protocols and PLCs rather than technologies affording full computer control.

Sensors and connected systems, such as wireless sensor and actuator networks, are being integrated into the management of industrial environments, such as those for water treatment, electric power and factories. The integration of automation, communications and networking in industrial environments is an integral part of the growing IoT. Information technology or operational technology convergence enables more direct control and more complete monitoring, with easier analysis of data from complex systems anywhere in the world.

Operational technology’s modernization through IT integration brings concerns of security. Many OT systems were never designed for remote accessibility and, as a result, the risks of connectivity were not considered. Such systems may not be regularly updated. The vulnerabilities of OT systems can leave organizations and critical infrastructure at risk of industrial espionage and sabotage (Rouse, 2016).

IT and OT are converging in numerous important industries, such as health care, transportation, defense, energy, aviation, manufacturing, engineering, mining, oil and gas, natural resources and utilities. Information technology leaders who are impacted by the convergence of IT and OT platforms should consider the value and risk of pursuing alignment between IT and OT, as well as the potential to integrate the people, tools and resources used to manage and support both technology areas.
3.8.1 IT and OT: A Disappearing Distinction

The convergence of IT and OT in IoT has been going on for a while, and there isn’t a strict division between them in the real world. In many businesses with lots of heavy machinery or other forms of OT, IT departments will often be closely involved because of the critical role of the technology, as well as the ongoing technological convergence.

However, in some areas, the distinction is still clear. An IT worker won’t repair a high-tech oil drill and an engineer won’t take care of the technologies to assemble cars or sit in a meeting on using predictive analytics to protect the corporate network from cyber threats. Nonetheless, the lines are blurring (i-SCOOP (b)).

3.8.2 How Does IoT Bring IT and OT Together?

The link between the IoT and IT or OT is clear. The IoT is mainly about automating processes using connected devices with a capacity to gather, receive and send information, embed intelligence and connectivity into devices and set up processes and applications that open up a realm of new possibilities with the proper tools to analyze data, automate and write applications, putting these devices to work (i-SCOOP (b)). Figure 3.19 shows how IT and OT are converging in utilities.

The convergence of IT and OT is inevitable in the industrial Internet of Things (IIoT). Convergence is about technology but it is also about new ways of thinking. This is a challenge when two worlds, which have worked separately and with completely different systems, technologies and vendors meet in the context of IIoT (i-SCOOP (b)). Figure 3.20 shows the various components of IT and OT and their convergence in IIoT.

3.8.2.1 When Worlds Collide—Industrial Internet of Things

As mentioned above, until recently, IT and OT have had fairly separate roles within an organization. However, with the emergence of the Industrial Internet and the integration of complex physical machinery with networked sensors and software, the lines are blurring.

![2014 Utility IT/OT Convergence Survey](image)

**FIGURE 3.19** IT and OT in utilities (i-SCOOP (b)).
The scope of Industrial Internet has exploded into more general Internet connectivity, as opposed to the historically closed systems that relied on physical security to ensure integrity. With the shift from closed to open systems comes an even greater interdependence and overlap between OT and IT, along with new security concerns (Desai, 2016).

### 3.8.2.2 New Concerns for Both Sides

Greater connectivity and integration are obviously beneficial for smart analytics and control, but more connections and networked devices mean more opportunities for security holes. While security has always been a priority for IT and OT in traditional systems, these networked systems are presenting new scenarios and risk profiles to both sides. Information technology currently needs to start thinking like OT and vice versa (Desai, 2016).

#### 3.8.2.2.1 New Concerns for IT

**Greater scope of impact:** A security incident in a more traditional enterprise environment will have detrimental results, but the effects of an incident on an industrial system are on a completely different scale. Consider the repercussions if an electricity grid goes offline, or if a car’s engine control system is hacked and the driver is no longer in complete control.

**Physical risks and safety:** Unlike more traditional enterprise systems, networked industrial systems bring an element of physical risk to the table that IT teams have not had to consider. An interruption in service or machine malfunction can result in injury to plant floor employees or the production of faulty goods, potentially harming end users.

**Outdated systems or custom configurations:** IT is used for frequent and consistent software patches and upgrades, but industrial environments tend to be more systemic, and one small change can trigger a domino effect. As a result, many legacy plant control systems may be running outdated operating systems that cannot easily be swapped out or a custom configuration that isn't compatible with standard security packages (Desai, 2016).
3.8.2.2 New Concerns for OT

**Physical risks and safety:** OT teams have been implementing safety measures into industrial systems for decades, but are currently facing threats potentially outside their control. Taking machines and control systems out of a closed system brings the threat of hacked machines, and this could potentially injure employees (e.g., overheating, emergency shut-offs overridden, etc.).

**Productivity and quality control:** Losing control of the manufacturing process or any related devices is a major problem for OT. Consider the ramifications if a malicious party shut down a plant, halting production entirely, or reprogrammed an assembly process to skip a few steps, resulting in a faulty product that could injure end users.

**Data leaks:** Data breaches are a long-standing concern for traditional IT teams, but OT teams are used to working with closed systems. Given the nature of the types of industrial systems that are coming online, such as utilities, aviation and automobile manufacturing, ensuring the privacy of transmitted data is critical.

**Working with IT:** While many in OT see the benefits of moving away from closed systems and increasing connectivity, the perceived lack of IT experience and potential solutions for their security concerns is causing some to resist integration (Desai, 2016).

3.8.2.3 Finding Common Ground

While OT and IT may have different backgrounds framing their concerns about the transformation caused by the IIoT, the main underlying concern for both parties is retaining control of systems and machines and ensuring the safety of their employees and customers. To make both sides happy, key components of any security solutions should include the following:

- Identifying and authenticating all devices and machines within the system, both in manufacturing plants and in the field, to ensure only approved devices and systems are communicating with each other. This would mitigate the risk of a hacker inserting a rogue, untrusted device into the network and taking control of any systems or machines.
- Encrypting all communications between devices to ensure the privacy of the data being transmitted.
- Ensuring the integrity of the data generated from these systems. Smart analytics are a major driver in the adoption of the industrial Internet, but those analytics are worthless if the data are inaccurate.
- Enabling the ability to perform remote upgrades down the road, if the manufactured goods contain software or firmware themselves, and ensuring the integrity of those updates.

The separation of OT and IT will continue to disappear. In the meantime, each side must consider the other’s expertise and point of view and work together to achieve the ultimate goal—a secure, productive Industrial Internet (Desai, 2016).

### 3.9 Data and Optimization across the Value Chain: IT, OT and Cyber-Physical Systems in “Smart Anything”

The CPS used by Industry 4.0 enable new capabilities in areas such as product design, prototyping and development, remote control, services and diagnosis, condition monitoring, proactive and predictive maintenance, track and trace, structural health and systems health monitoring, planning, innovation capability, agility, real-time applications and so on. Cyber-physical system offers Industry 4.0 personalization capabilities, real-time alerts and interventions, innovative service models, dynamic product improvement, increased productivity, higher uptime and new business models.

The new capabilities of Industry 4.0 lead to the “smart anything” phenomenon: from smart grids to smart energy, smart logistics, smart facilities, including smart buildings and smart plants, and smart services.
Industry 4.0 builds upon data models and data mapping across the product lifecycle and value stream. All the technologies in Industry 4.0 need to be integrated. As discussed in previous sections, the first integration (or convergence) is IT and OT. Without IT and OT convergence, there is no industrial transformation. The essence of IT and OT convergence revolves around data and data systems, processes and people or teams.

The IoT is an essential part of this process. In fact, it is safe to say that Industry 4.0 is only possible because of IoT, as the convergence of IT, OT and their backbones essentially boils down to an advanced and enhanced application of Internet, IT technologies and IT infrastructure impacted by IoT data (cloud infrastructure, server infrastructure, storage and edge infrastructure, etc.) (i-SCOOP (a)) (see Figure 3.21).

![Industry 4.0: the convergence of IT, OT and cyber-physical systems (i-SCOOP (a)).](image)
3.10 Industry 4.0 Principles: Horizontal and Vertical Integration

There is a difference between horizontal and vertical integration, but the goal is the same: ecosystem-wide data information is shared between various systems and across all processes, using data transfer standards and creating the basis for an automated supply and value chain.

3.10.1 Horizontal Integration in Industry 4.0

Horizontal integration refers to the integration of IT systems for and across the various production and business planning processes. Between these various processes, there are flows of materials, energy and information. They concern internal and external partners, suppliers, customers and other ecosystem members, from logistics to innovation, and stakeholders.

In other words, horizontal integration requires digitization across the full value and supply chain with an emphasis on data exchanges and connected information systems. This can be difficult, because many organizations still have disconnected IT systems. When we add seamless integration and data exchange with suppliers, customers and other external stakeholders, the picture becomes even more complex (Figure 3.22).

![Figure 3.22](image-url)  
Horizontal integration in Industry 4.0 (i-SCOOP (a)).
This type of thinking is still in its infancy; whether it concerns product data or information about other processes across the horizontal value chain (e.g., the path from supplier and production to end customer and/or other stakeholders or partners), there is still work to do. Nevertheless, it is critical for Industry 4.0 and for business overall.

The benefits and drivers of horizontally connected information systems are comparable to those in information management, as are the disadvantages if systems are not integrated. Both are concerned with customer service and satisfaction (with many customers in supply chains), planning, employee productivity and satisfaction, speed and so forth. Consider the information management challenges in an insurance scenario: if back-office information on, for instance, a claims process, is not connected with the front end, customer service agents can’t help the customer fast enough if he or she seeks information or help on the status of the process. It’s exactly the same in Industry 4.0 and manufacturing. We just have more stakeholders, more highly interdependent processes and stakeholders, far more processes and data.

Horizontal integration helps with horizontal coordination, collaboration, cost savings, value creation, speed as an enabler of smooth service and operations, faster time to market and worker efficiency, and helps to create horizontal ecosystems of value, based on information (Figure 3.23).

### 3.10.2 Vertical Integration in Industry 4.0

Whereas horizontal integration is about IT systems and flows in the supply or value chain and the various processes happening across it, vertical integration has a hierarchical level component. In other words, it’s about the integration of IT systems at various hierarchical production and manufacturing levels into one comprehensive solution.

These hierarchical levels are: the field level interfaces with the production process via sensors and actuators; the control level regulates both machines and systems; the process line level or actual production process level needs to be monitored and controlled; the operations level includes production

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**FIGURE 3.23** Horizontal integration in Industry 4.0/Horizontal ecosystems of value, based on information (i-SOCOOP (a)).
planning, quality management and so on; the enterprise planning level includes order management and processing, bigger overall production planning and so on (Figure 3.24).

Typical solutions and technologies in vertical integration include PLCs, which control manufacturing processes at the control level; SCADA, which enables various production process level and supervisory tasks in ICS; MES at the management level; intelligent ERP at the enterprise level, the highest level in the hierarchy. As mentioned earlier, MES plays a central role in the first stages of Industry 4.0 transformation as the digital hub of information and connectivity.

### 3.11 Basic Functions and Uses of CPS

Because CPS have the required decentralized intelligence, they are themselves able to assess situations, make decisions and prompt other CPS to perform actions when necessary. These behaviors are programmed, and CPS are ideally able to change and adapt themselves, thus revising, if not replacing, the hierarchical and vertical decision path, a hallmark of everyday manufacturing for decades.

In the past, components (especially sensors) recorded the actual state of the process and reported all relevant information to the central control unit. The state was analyzed at the control unit level and/or at the higher-ranking control system level, decisions were made, and the process was intervened, with the aid of actuators or manual actions.

This hierarchical and vertical communication is not meant to be replaced with the aid of CPS, but supplemented.
The three subsystems enable CPS to assume its new role include sensors, actuators and embedded systems and a microprocessor-based, decentralized intelligence. The CPS can record its current situation in the environment with the aid of integrated sensors. For example, a machine’s optical sensors can supply comprehensive information about the type and state of the workpieces to be processed. Actuators are used to execute actions. For example, a grapper that picks the selected workpieces is extended. At the same time, the decentralized intelligence evaluates the sensor information, as well as information flowing in from other CPS. Based on this, it makes its decisions and passes these on to its own actuators. At the same time, it contacts other CPS and prompts these to action.

The virtual image of CPS is not simply a snapshot of the current status and links. It also includes information about the entire lifecycle.

Even in the design phase, information emerges on geometry, mechanical properties, logical connections and sets of parameters. All other life cycle phases such as engineering, start-up and operation, including maintenance and service, provide additional information. Based on all this information, CPS can react to situations independently. Ideally, it can also use past information to be able to adapt decision rules to the new situation each time.

Based on this, each CPS can now have knowledge about its integration into the entire production facility. That can be used by the CPS to configure itself during start-up, automatically establish communication with its production partners (other CPS) and thus greatly reduce the costly start-up time. The optimization phase can be performed during the day-to-day production. In the process, the various CPS can optimize themselves due to their intelligence. In the simplest case, this can be an independent discovery of the optimum operating point. In more complex cases, it can be a choice between predefined or even newly determined procedure scenarios. If problems occur at one time in the production sequence, for instance, if a machine has malfunctioned or required material is missing, alternative strategies that “heal” the process and keep it running can be developed.

However, such problems should be avoided or at least made visible with good lead time by CPS generating early warning information, making preventive maintenance possible by supporting condition monitoring. In decentralized communication between various CPS, it is not absolutely necessary for this to be directly between one CPS and another. Rather, a multitude of communicative CPS platforms will use their services and applications to network people, external systems and CPS with each other. Two communication channels, i.e., direct CPS exchange and the path via CPS platforms, complement each other (see Figure 3.25). To give an example, a CPS transport container can immediately enter into

![Diagram](image_url)

**FIGURE 3.25** CPS platforms linking individual CPS, external systems and the operator. (From Amberg, J., Industry 4.0 and Cyber-Physical Systems—Classification and Practical Example, Managing Director of halstrup-walcher GmbH, Format Change in Machine Building, Kirchzarten, Germany, 2015.)
a communication exchange at some stages of production, because it can technically do this. All other
stages of production that do not have CPS functionality are controlled via a CPS platform. The CPS
transport container can thus make decentralized requests for supplies in all production areas relevant to
it and locally trigger operations (Amberg, 2015).

3.12 Practical Example of a Cyber-Physical System:
The Self-Modifying Machine
The machines of the future will act as CPS themselves and will be a combination of cyber-physical
subsystems. Consider the example of positioning systems. With their sensors (absolute encoders for posi-
tioning) and actuators (gearbox, motor, engine control) for moving positioning objects, they will have
all the components required to represent an independent CPS, together with decentralized intelligence
(embedded system).

A CPS positioning system can naturally be conventionally integrated into machine procedures as
shown in Figure 3.26. At this juncture, the positioning system automatically navigates to the new position
according to the specification of the next target position (because of the machine control) and in doing
so, independently minimizes “drag errors” (deviation from the designated position during navigation). If
drag errors are very large, high-quality positioning systems will decide for themselves whether the situa-
tion is a “block movement” (obstacle) they should brake for or whether the positioning movement should
be accelerated due to detected dirt and sluggishness to overcome the contamination. The positioning task
is optimally executed—but it is requested from above by the machine control unit. In terms of Industry
4.0, this optimally supports the machine’s role as a CPS as it establishes contact with the in-house trans-
port systems, the nearby machines and the parts supplier (Amberg, 2015).

FIGURE 3.26 Conventional hierarchical integration of a positioning system into a machine that itself acts as a CPS.
(From Amberg, J., Industry 4.0 and Cyber Physical Systems—Classification and Practical Example, Managing Director of
halstrup-walcher GmbH, Format Change in Machine Building, Kirchzarten, Germany, 2015.)
As shown in Figure 3.27, the CPS positioning system can be embedded by breaking through the hierarchical structures of the machine control unit. Instead of a vertical exchange with the machine control, the CPS positioning system enters into a direct exchange with decentralized components (Amberg, 2015).

Consider the example of a new format being detected by a sensor. An optical sensor in a packaging line detects that a shift must be made to a new packaging size because of a new product format. The sensor gives the positioning system a direct decentralized specification of the new target positions; with this information, the guide rail, packaging tools and if necessary the inspection camera are moved to the new position. The higher-level machine control and the operator at his or her panel are continuously informed of the actual position and are notified when target positions are reached. This information is accompanied by reports that make preventive maintenance possible. Another example is the independent coordination of two synchronously running positioning systems without the need to incorporate the control unit.

This decentralized embedding of the positioning system as an independent CPS leads to increased adaptability and responsiveness. The central machine control unit can focus on its own CPS tasks and on the machine’s integration into the overall production process. The person in charge can intervene via the control panel if necessary or concentrate on the optimization of the production process instead of having to trigger simple and regular processes such as format changeovers.

The ability to manage format changes at both levels described above, i.e., modification of the machine user’s production and modification during machine design, will be a crucial factor in competitiveness. What mostly concerned industry’s major groups yesterday is currently the focus of medium-sized companies. Everyone involved needs to keep up. To paraphrase Albert Einstein: “Life is like riding a bicycle. If you stop moving, you will fall off” (Amberg, 2015).

### 3.13 Digital Platforms

As customer experience moves deeper into the organization ethos, enterprises are looking at making a higher impact on this “new normal” behavior of their customers. What initially started as front-end, multichannel play is currently penetrating the IT systems. Digital platforms are turning out to be the pedestal
for digital ecosystems. These platforms are shaping the technology landscape and have the potential to touch every aspect of human lives. They bridge businesses, influence behaviors, build communities and can outline an entire ecosystem around themselves.

Needless to say, this paradigm shift has received the interest of technology companies and digital leaders. They are developing new technology platforms and formulating new business models. While it may not be imperative for a company to own its own platform ecosystem, it is essential to have a robust platform strategy and the business know-how to execute it. If harnessed well, this global economic revolution will transform the way business is done for many years to come. Enterprises used to have large monolithic platforms, which served only one or two purposes. With the advent of mobile and digital, they are building customized platforms to suit their industry process and needs, as well as delivering personalized and contextual information to their customers. The new platforms need to touch the consumer via mobile devices, engage in product awareness, monitor campaigns, undertake loyalty management and analyze data, along with providing personalized offers (Shankavaram and Gartner, 2016).

3.13.1 Need for a Digital Platform

Systems and services are becoming digitally aware, and enterprises are integrating platforms that can enable collaboration between businesses. Today, platform technologies are available to orchestrate heterogeneous channels, systems and services. Context awareness is building on personalization and localization to throw exciting opportunities at businesses. The innovators have moved on from knowing “who” their customers are to “where” they are, “how” are they doing, “what” they did before and “what” are they likely to do next. As indicated in Figure 3.28, this intelligence enables an organization to connect with the customer at the right time, right place and at the right price from the right channel. Organizations need to be ready to remodel their businesses to take advantage of new opportunities (Shankavaram and Gartner, 2016).

To execute transformation, organizations need to pull together an ecosystem across all their boundaries, aligning marketing, sales, operations, support and all other functions. This capability allows organizations to create and maintain an agile digital platform where innovative products and solutions can be rolled out in an efficient and adaptive manner (Shankavaram and Gartner, 2016).

![Figure 3.28](image_url)  
**FIGURE 3.28** Digital connects everything. (From Shankavaram, D. and Gartner, Travelling to the future with Digital Platforms, Capgemini, Consulting Technology Outsourcing, Capgemini India Pvt Limited, 2016.)
3.13.2 Digital Platforms

- Provide an integrated service view of businesses and unified workflows.
- Seamlessly incorporate transformations such as context, personalization and proximity.
- Promote constant learning and thinking of customer behaviors.
- Permit real-time decision-making based on the business possibilities exposed by various systems.
- Safeguard user data, user context and user presence.
- Suggest innovations to solve business problems.
- Allow multiple partners to orchestrate an integrated solution.
- Can run and sustain a successful operations model.
- Understand and predict customers.
- Target and reach customers.
- Provide personalized experiences.
- Sense environment and context.
- Rapidly orchestrate workflows.
- Bring synergy between various customer-centric themes (Shankavaram and Gartner, 2016).

3.13.3 Building a Digital Business Technology Platform

A digital business is supported by technology platforms in five areas (Shankavaram and Gartner, 2016):

- Information systems platform: supports the back office and operations, such as ERP and core systems.
- Customer experience platform: contains the main customer-oriented elements, such as customer and citizen portals, multichannel commerce and customer apps.
- Data and analytics platform: contains information management and analytical capabilities; data management programs and analytical applications fuel data-driven decision-making and algorithms automate discovery and action.
- IoT platform: connects physical assets for monitoring, optimization, control and monetization; capabilities include connectivity, analytics and integration to core and OT systems.
- Ecosystems platform: supports the creation of, and connection to, external ecosystems, marketplaces and communities; application programming interface (API) management, control and security are its main elements.

3.13.3.1 How to Build a Digital Business Technology Platform

Regardless of the variety of digital business, most enterprises do not have the technology components to support the new capabilities and models.

A digital business requires much more than technology (e.g., leadership, talent and skills and new business models). However, from a technology perspective, the chief information officer (CIO) and the IT team are generally expected to lay out the technology foundation (see Figure 3.29). At a minimum, the IT organization needs to be able to design the “big picture” of all the new information and technology capabilities required to support digital business. Information technology can then work with the rest of the organization to define who will build or fund or support or own these major components (Shankavaram and Gartner, 2016).

When they are building a digital platform, CIOs and IT leaders need to do the following (Shankavaram and Gartner, 2016):

- Determine which of the five platforms need to be implemented or renovated and when.
- Do a “checklist” exercise to determine what parts are missing or need to be improved and modernized.
- Start with prototyping and pilots while completing the renovation of the information systems, customer experience and data and analytics platforms.
3.13.4 Toward Digital Platforms

If enterprises are to generate value in the digital world, they must operate closer to the market, deeply integrating customers, partners and physical products in their business model. This means transforming the technology landscape, with technology seen as a platform to digitally connect people, businesses and physical products into value-creating networks.

This requires an outside-in perspective, integrating customers, products, partners and other stakeholders in a value ecosystem in a digital way. Interaction and engagement layers must connect the different participants. At the same time, however, organizations still need to connect this to an inside-out perspective, aligning internal operational processes with the customer experience and managing enterprise data.

Some major cross-cutting concerns in the move toward digitalization, as shown in Figure 3.30, are security, integration, insights and analytics, reporting and collaboration (Merckx, 2016).

FIGURE 3.29 Digital business technology platform. (From Shankavaram, D. and Gartner, Travelling to the future with Digital Platforms, Capgemini, Consulting Technology Outsourcing, Capgemini India Pvt Limited, 2016.)

As organizations cannot predict and control technological developments, they need to experiment, measure and learn, to be able to adapt a platform in an agile way to accommodate trends in the outside world (Merckx, 2016).

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