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Industry 4.0: state of the art and future trends

Li Da Xu[a]*, Eric L. Xu[b] and Ling Li[a]

[a]*Department of Information Technology & Decision Sciences, Old Dominion University, Norfolk, VA, USA;* [b]*Curtis L. Carlson School of Management, University of Minnesota, Minneapolis, MN, USA*

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Rapid advances in industrialisation and informatisation methods have spurred tremendous progress in developing the next generation of manufacturing technology. Today, we are on the cusp of the Fourth Industrial Revolution. In 2013, amongst one of 10 ‘Future Projects’ identified by the German government as part of its High-Tech Strategy 2020 Action Plan, the Industry 4.0 project is considered to be a major endeavour for Germany to establish itself as a leader of integrated industry. In 2014, China’s State Council unveiled their ten-year national plan, Made-in-China 2025, which was designed to transform China from the world’s workshop into a world manufacturing power. Made-in-China 2025 is an initiative to comprehensively upgrade China’s industry including the manufacturing sector. In Industry 4.0 and Made-in-China 2025, many applications require a combination of recently emerging new technologies, which is giving rise to the emergence of Industry 4.0. Such technologies originate from different disciplines including cyber-physical Systems, IoT, cloud computing, Industrial Integration, Enterprise Architecture, SOA, Business Process Management, Industrial Information Integration and others. At this present moment, the lack of powerful tools still poses a major obstacle for exploiting the full potential of Industry 4.0. In particular, formal methods and systems methods are crucial for realising Industry 4.0, which poses unique challenges. In this paper, we briefly survey the state of the art in the area of Industry 4.0 as it relates to industries.

Keywords: Industrie 4.0; Industry 4.0; Made-in-China 2025; cyber-physical systems; IoT; cloud computing; blockchain; manufacturing; industrial integration; industrial information integration; interoperability; enterprise architecture; SOA; emerging technology

1. Introduction

Industrie 4.0 was initially introduced during the Hannover Fair in 2011; furthermore, it was officially announced in 2013 as a German strategic initiative to take a pioneering role in industries which are currently revolutionising the manufacturing sector. Industrie 4.0 is also called Industry 4.0 which symbolises the beginning of the Fourth Industrial Revolution (Alexopoulos et al. 2016; Qin, Liu, and Grosvenor 2016; Li 2017). Industry 4.0 represents the current trend of automation technologies in the manufacturing industry, and it mainly includes enabling technologies such as the cyber-physical systems (CPS), Internet of Things (IoT) and cloud computing (Hermann, Pentek, and Otto 2016; Jasperneite 2012; Kagermann, Wahlster, and Helbig 2013; Lasi et al. 2014; Lu 2017a, 2017b). According to GTAI (2014), Industry 4.0 represents the technological evolution from embedded systems to cyber-physical systems. In Industry 4.0, embedded systems, semantic machine-to-machine communication, IoT and CPS technologies are integrating the virtual space with the physical world; in addition, a new generation of industrial systems, such as smart factories, is emerging to deal with the complexity of production in cyber-physical environment (GTAI 2014). Research illustrates how Industry 4.0 represents the approach of the Fourth Industrial Revolution, upon which Information and Communication Technologies (ICT) form the infrastructural foundation for tomorrow’s innovative industrial technologies. In this new ICT driven technological evolution, embedded systems, IoT, CPS, Industrial Integration and Industrial Information Integration are playing important roles.

Today, we are at the cusp of the Fourth Industrial Revolution in which the worlds of production and network connectivity are integrated through IoT and CPS in order to make Industry 4.0 a reality (GTAI 2014). During the First Industrial Revolution, mechanical production facilities were developed with the help of water and steam powers. During the Second Industrial Revolution, mass production was realised with the help of electrical energy. During the Third Industrial Revolution, electronic and information technologies were introduced that furthered production automation.

*Corresponding author. Email: lxu@odu.edu

During the Fourth Industrial Revolution, the use of cyber-physical systems (CPS) has triggered a paradigm shift in industries, in particular the manufacturing sector.

During the Third Industrial Revolution, a group of researchers from IEEE, IFIP, IFAC and relevant industries came together to create the roadmap for advancing the development of manufacturing systems (Kaynak 2005; Wilamowski 2005; IFAC 2007; Xu 2007). In 2005, new opportunities in the field of industrial informatics were discovered by Wilamowski, Kaynak and other researchers (Kaynak 2005; Wilamowski 2005; Carcano et al. 2011). As a process of industrial integration (Xu et al. 2016) and driven by ICT, a shift from industrial electronics to industrial informatics was found where the industrial application of ICT has been emphasised more than ever before. Meanwhile, one of the new trends in Critical Infrastructures including industrial ICT infrastructure shows its intensifying interconnections via ICT (Kaynak 2005; Wilamowski 2005; Carcano et al. 2011).

Over the last few years, Industry 4.0 has emerged as a promising technology framework used for integrating and extending manufacturing processes at both intra- and inter-organisational levels. This emergence of Industry 4.0 has been fuelled by the recent development in ICT. The developments and the technological advances in Industry 4.0 will provide a viable array of solutions to the growing needs of informatisation in manufacturing industries. This viability has been evidenced by the fact that a growing number of enterprises world-wide have explored the benefits of digitising enterprises' horizontal and vertical chains and adopted Industry 4.0, in the process of becoming leading digital enterprises in tomorrow's complex industrial ecosystems (PWC 2016).

In the global economy and in global business operations, we have witnessed that there has been a need for Industry 4.0 to dramatically increase the overall level of industrialisation, informatisation and manufacturing digitisation to achieve greater efficiency, competency, and competitiveness. It is well recognised that Industry 4.0 has an important long-term strategic impact on global industrial development. Due to the importance of this subject, there has been a growing demand for research regarding Industry 4.0 in order to provide insights into the issues, challenges, and solutions related to the design, implementation and management of Industry 4.0.

This paper is intended to provide readers with a new perspective on Industry 4.0, an emerging technology for industrial organisations, while the dialogue amongst researchers and practitioners in both industry and Industry 4.0 research areas grows and coalesces. The objective of this paper is to introduce the communities within industrial sectors to current developments and future opportunities that exist in the exciting field of Industry 4.0; however, this survey is by no means meant to be exhaustive. In Section 2, we briefly discuss the evolution from Industry 1.0 to Industry 4.0 in terms of four milestones. Section 3 describes major enabling technologies in Industry 4.0 development, Section 4 discusses research challenges and directions, and Section 5 concludes this paper.

2. The evolution from Industry 1.0 to Industry 4.0

In order to understand the progression of industry, Figure 1 shows the evolution from Industry 1.0 to Industry 4.0, as well as the ICT roadmap proposed by Wilamowski, Kaynak, Xu and other researchers (Kaynak 2005; Wilamowski 2005; Xu 2015, 2016; Xu et al. 2016) on industrial integration and industrial information integration for the emerging era of IoT and CPS.

The First Industrial Revolution began at the end of the eighteenth century and early nineteenth century, which was represented by the introduction of mechanical manufacturing systems utilising water and steam power. The Second Industrial Revolution started in the late nineteenth century, symbolised by mass production through the use of electrical energy. The Third Industrial Revolution began in the middle of twentieth century and introduced automation and microelectronic technology into manufacturing. These advances in manufacturing technologies were closely related to ICT. In the Third Industrial Revolution, the advancement of ICT was at the core of every major shift of the manufacturing paradigm. For example, the widespread adoption of computer numerical control (CNC) and industrial robots made flexible manufacturing systems (FMSs) possible; the technologies for computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided processing planning (CAPP) made computer integrated manufacturing (CIM) possible (Feng, Li, and Cen 2001). Most recently, manufacturing has been on the brink of the Fourth Industrial Revolution. The introduction of CPS will be one of the most revolutionary changes in the Fourth Industrial Revolution. Industry 4.0 is described as a fourth industrial revolution since the first industrial revolution during the late eighteenth century. Industry 4.0 is mainly represented by CPS, IoT and cloud computing (Jasperneite 2012; Kagermann, Wahlster, and Helbig 2013; Lasi et al. 2014; Hermann, Pentek, and Otto 2016; Moeuf et al. 2017), however, it will also rely on smart devices in addition to IoT, CPS, cloud computing and BPM (business process management). Although the Third Industrial Revolution also focused on the automation of machines and processes (Tan et al. 2010), Industry 4.0 focuses more on the end-to-end digitisation and the integration of digital industrial ecosystems by seeking completely integrated solutions.

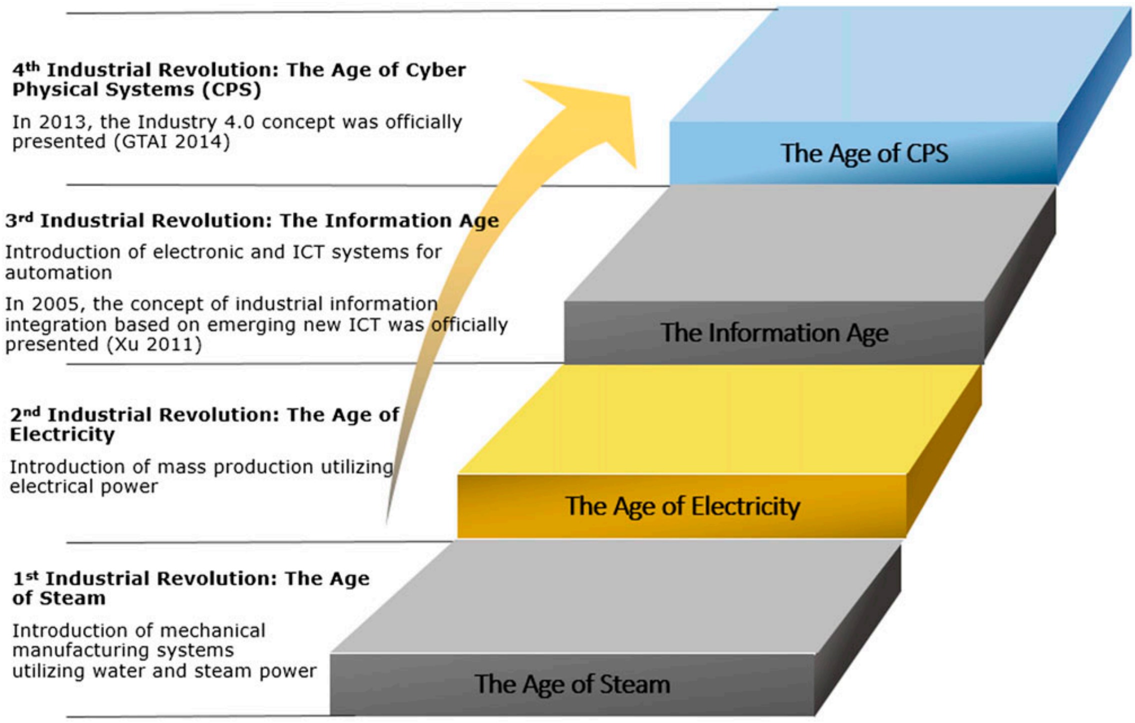

Figure 1. The evolution from Industry 1.0 to Industry 4.0.

In Industry 4.0, IoT is expected to offer promising transformational solutions for the operation and role of many existing industrial systems within the digital enterprises of tomorrow's complex industrial ecosystems. According to GTAI (2014), IoT has been finding its way into production all while revolutionising the existing manufacturing systems; thus, it is considered to be a key enabler for the next generation of advanced manufacturing, Industry 4.0 (Varghese and Tandur 2014; Trappey et al. 2017). Most notably, IoT can enable the creation of virtual networks to support the smart factory in Industry 4.0 (Oesterreich and Teuteberg 2016; Peruzzini et al. 2017).

Cloud-based manufacturing is a technology which can contribute significantly to the realisation of Industry 4.0 (Thames and Schaefer 2016). Cloud manufacturing, similar to cloud computing, uses a network of resources in a highly distributed way. Manufacturing-as-a-Service (MaaS) has been gaining attraction in the manufacturing industry.

CPS is the core foundation of Industry 4.0 (Varghese and Tandur 2014; De Silva and De Silva 2016; Kim 2017). According to Monostori (2014), one of the most significant achievements in developing ICT is represented by CPS. CPS are the systems of collaborating computational entities that are in intensive connection with the surrounding physical world and its on-going processes; furthermore, these systems, provide and use data-accessing and data-processing services available on the Internet to achieve the aforementioned ends. In CPS, physical and software components are deeply intertwined, each operating on different spatial and temporal scales, and interacting with each other in a myriad of ways that change with context (Wikipedia 2017a). CPS present a higher level of integration and coordination between physical and computational elements (Gürdür et al. 2016; Wikipedia 2017a), as the current trend reveals a technological evolution from embedded systems to CPS. Research indicates that with the introduction of CPS, machines will be able to communicate with each other and decentralised control systems will be able to optimise the production.

Industry 4.0 generally comprises many complex components, and has broad applications in numerous industrial sectors. At present, one of the challenges we face is to make use of cutting-edge ICT as well as engineering technology to make Industry 4.0 successful (Mousterman and Zander 2016).

3. Enabling technologies

Various technologies or techniques can be used for implementing Industry 4.0. These technologies include CPS, IoT, cloud computing, blockchain, industrial information integration and other related technologies (Li 1999; Jasperneite 2012; Kagermann, Wahlster, and Helbig 2013; GTAI 2014; Lasi et al. 2014; Arnold, Kiel, and Voigt 2016; Hermann, Pentek, and Otto 2016; Ivanov and Muminova 2016a, 2016b; Lu 2016; Oliveira and Álvares 2016; Thames and Schaefer 2016; Khan and Khan 2017a; Moeuf et al. 2017). In this section, we introduce the selected technologies that are particularly significant for Industry 4.0. However, the coverage of enabling technologies in this section is by no means meant to be exhaustive.

3.1 *IoT and related technologies*

When the term, Internet of Things (IoT), first emerged, it was referred to uniquely identifiable interoperable connected objects using radio-frequency identification (RFID) technology (Ashton 2009; Xu, He, and Li 2014). Connecting RFID reader to the Internet, the readers can automatically and uniquely identify and track the objects attached with tags in real-time. This is Internet of Things (IoT). Later on, the IoT technology was used with other technologies, such as sensors, actuators, the Global Positioning System (GPS) and mobile devices that are operated via Wi-Fi, Bluetooth, cellular networks or near field communication (NFC). Therefore, a more recent definition of IoT is as follows:

> a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual 'Things' have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network. (van Kranenburg 2008)

The foundation of IoT can be considered as a global network infrastructure composed of numerous connected devices that rely on sensory, communication, networking and information processing technologies (Tan and Wang 2010; Xu, He, and Li 2014; Mao et al. 2016; Liu et al. 2017). RFID and wireless sensor networks (WSN) are viewed as the two most important devices that enable the IoT network. RFID technology allows microchips to transmit the identification information to a reader through wireless communication (Xu, He, and Li 2014; Alyahya, Wang, and Bennett 2016). Using RFID readers, users are able to distinguish, track and monitor any objects tagged with RFID tags automatically (Jia et al. 2012). RFID has been applied in many different industries, such as transportation, package delivery, healthcare, materials management, retailing, defence, etc. WSN, on the other hand, applies interconnected intelligent sensors for sensing and monitoring. Numerous applications of WSN have been reported that include industrial monitoring, environmental monitoring, transportation monitoring, healthcare monitoring and others (van Kranenburg et al. 2011; Li, Xu, and Wang 2013; Fan et al. 2014; He and Xu 2014; Kang et al. 2014; Xu et al. 2014; Liu et al. 2016; Yin et al. 2016; Yang et al. 2018). The advances in both RFID and WSN significantly contribute to the development of IoT (Xu, He, and Li 2014). Figure 2 illustrates technologies and devices used to support IoT. The key technologies include RFID and WSN, and other relevant technologies such as barcodes, smart phones, cloud computing, location-based service, SOA, near field communication and social networks (Uckelmann, Harrison, and Michahelles 2011; Li, Xu, et al. 2012; Tao et al. 2013; Wang et al. 2014; Xu, He, and Li 2014).

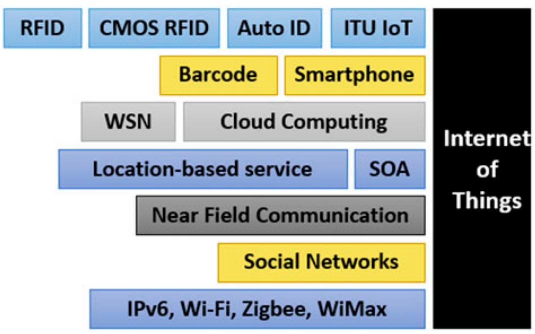

Figure 2. Technologies and devices used to form an extensive network for supporting IoT (Xu, He, and Li 2014).

Industry 4.0 also known as smart manufacturing and cognitive manufacturing offers new opportunities for manufacturing firms to analyse and use design, production, sourcing and inventory data to help them realise their modernisation vision. Industry 4.0 uses cognitive computing techniques along with Industrial IoT (IIoT) applications; it applies data science and analytical models to analyse real-time data from multiple machines, processes and systems; and then it automates manufacturing accordingly. Thus far, various manufacturing industries have applied IoT and IIoT to advance production, distribution, transportation, service and maintenance in the manufacturing process (Tao et al. 2016).

Industry 4.0 combines intelligent sensors, artificial intelligence, and data analytics to optimise manufacturing in real time. With the advances in sensor network technologies, wireless communication, and other emerging technologies, more and more networked things, or smart objects, are being involved in IoT. Meanwhile, these IoT-related technologies have also made a significant impact on new ICT and CPS thus paved the way for the realisation of Industry 4.0. Figure 3 presents advances in RFID, WSN and IoT. Today RFID, WSN and IoT are used to form a solid technological foundation for supporting CPS as well as the emerging new ICT. As a result, Industry 4.0 is capable of developing a new generation of manufacturing systems that integrate and synchronise real-time data between the physical objects and the cyber computational space.

Below are some recent IoT applications in manufacturing industries.

IoT usage in the product lifecycle management. In IoT applications in manufacturing industry, Product Lifecycle Management (PLM) collects and manages data on product definition, process and decision across the entire product development stage. Unique identifiers for products or parts are important for PLM applications during the predefined lifecycle because products in PLM are disposed not only at an intra-organisational but also an inter-organisational level, in a distributed, mobile and collaborative environment. Thus, it is crucial to support the integration of distributed and heterogeneous product data covering different lifecycle stages with a configurable and flexible pattern. Due to the volume of heterogeneous data and a quickly changing environment, the involved data and information can be complicated for exchanging and sharing purposes. Cai et al. (2014) set up a flexible information model, as well as a configurable and open software platform, for IoT-based applications that cover the entire product lifecycle in order to integrate heterogeneous and distributed product information for manufacturing within and across organisations. This application also provides a base for further smart interactions, which are required in Industry 4.0 environment. A comprehensive

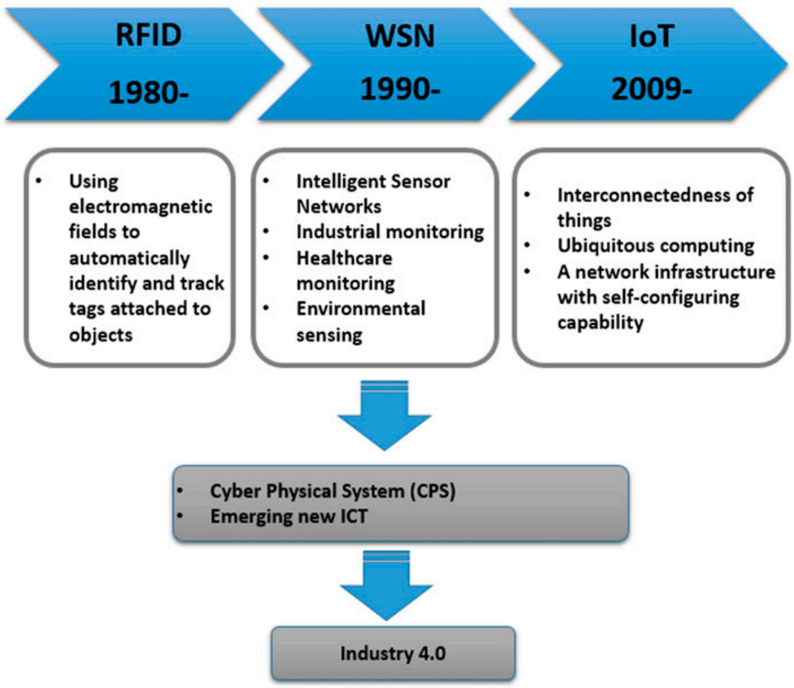

Figure 3. IoT related technologies made a significant impact on new ICT and paved the way for the realisation of Industry 4.0.

solution covering model and platform has been proposed to build an IoT-based Configurable Information Service Platform (ICISP) for the design, development and execution of Industry 4.0 applications in a mobile environment (Cai et al. 2014).

Merging IoT into industrial manufacturing systems. Changing trends of manufacturing paradigms have been explored by many researchers (Li 2000, 2017; Li and Li 2000). Bi, Xu, and Wang (2014) have analysed the needs of modern manufacturing and the features of IoT, and studied how modern manufacturing can benefit from the adoption of IoT infrastructure. There are three layers in the IoT environment; namely IoT platform layer, IoT application layer, and IoT industry solutions layer. The IoT platform layer connects various devices to receive and transmit data, and then streams information from the devices to the application layer. The application layer evaluates equipment status and integrates IoT with cognitive techniques such as data analytics, automation, machine learning to evaluate the dynamic complex factors that contribute to production. Data analytics using data collected through IoT network help expedite timely decision-making. The industry solutions layer adds the domain knowledge to the application layer. Industry-specific requirements, analytical procedures, knowledge management experience are tailored to the manufacturing process (IBM 2017). The multi-layer IoT system can be targeted to reach an optimal balance of efficiency and flexibility that help reduce cost and increase customisation. For example, a cement production company applied IoT technology with advanced machine learning algorithms to estimate energy consumption trend. The application optimised the company's energy consumption level and reduced energy consumption by 10%.

3.1.1 *RFID*

RFID is one of the cornerstones of IoT, a concept coined based on the RFID-enabled identification and tracking technologies. Since the 1980s, RFID has been used to identify and track objects, and widely applied in various industries, including manufacturing (Li 2013; Zhai et al. 2016). An RFID system can provide sufficient real-time information about things in IoT. RFID is a technology that makes use of wireless communication. Although RFID was initially developed for tracking and identification purposes, growing interest in many other possible applications has led to the development of a new range of wireless sensor devices based on RFID. In many cases, the automatic and continuous sensing capabilities of RFID can eliminate the need for human labour in the data collection process and enable more automated factories.

For RFID adoption through IoT, some challenges exist including signal interference, collision of RFID readings, integration, and standardisation, etc. The increasing use of RFID devices requires RFID security guaranteeing safety from multiple angles such as manufacture, privacy protection, business processes and others. Although RFID technology has been successfully used in many industrial sectors, the technology is still evolving.

3.1.2 *Wireless Sensor Networks (WSN)*

Wireless communication will play a key role in enabling Industry 4.0 systems and technology (Varghese and Tandur 2014). WSN is one of the most significant technologies of the twenty-first century. A WSN is a system comprised of radio frequency (RF) transceivers, sensors, microcontrollers, and power sources (Li and Xu 2017; Wikipedia 2017b). WSNs are the most important infrastructure for the implementation of IoT (Chi et al. 2014; Li et al. 2014; Yan et al. 2014; Bag et al. 2016; Panda, Mishra, and Ratha 2016; Finogeev and Finogeev 2017). Various hardware and software systems are available to WSNs: (1) Internet Protocol version 6 (IPv6) makes it possible to connect an unlimited number of devices. A single numbering scheme including IPv6 can make it possible to identify every single object; (2) WiFi and Wimax provide high-speed and low cost communication; (3) Zigbee, Bluetooth and RFID provide the communication in low-speed and local communication; (4) A mobile platform offers communication for anytime, anywhere, about anything.

As Figure 2 shows, both WSN and RFID are used to form an extensive network for supporting IoT. The main difference between the two is that WSN allow different network topologies and multi-hop communication, while RFID devices have no cooperative capabilities. The integration of WSN and RFID empowers IoT in the implementation of industrial services and the further deployment of services in extended applications.

In the research field of WSNs, most of the ongoing work focuses on energy efficient routing, aggregation, and data management algorithms. Other topics include the large-scale deployment, semantic integration of massive data (Sabar, Jayaweera, and Edirisuriya 2016; Xiao et al. 2014, 2016), and security (Li and Xu 2017). To achieve ambient intelligence, major technological innovations are required. These include governance, interoperability, standardisation, and efficient and secure communication protocols. Research challenges include enabling device adaptation, autonomous behaviour, intelligence, robustness and reliability (Xu, He, and Li 2014).

3.1.3 *Ubiquitous computing*

IoT is also known as ubiquitous computing, ambient intelligence and distributed electronics. In IoT, a virtual computer model can be seamlessly integrated with physical networks of objects (Ding et al. 2013; Xu et al. 2017). Ubiquitous computing is enabled by smart devices. Smart devices are capable of integrating devices, organisations, and information systems for data sharing and exchange; real-time monitoring; and using anything, anywhere, anytime communication to sense, capture, measure and transfer data. For individual smart devices, their performance has been improved greatly. They have become powerful, versatile, and intelligent enough to deal with changes and complexity. For the networked system, simple devices without superior computation capability can be integrated, thus abundant information can be acquired for real-time decision-making.

3.2 *Cloud computing*

Cloud computing is a computing technology which offers high performance and low cost (Zheng et al. 2014; Mitra et al. 2017). Virtualization technology provides cloud computing with resource sharing, dynamic allocation, flexible extension, and numerous other advantages. A large volume of data can be uploaded to a cloud computing centre for storage and computation, which facilitates manufacturing and production.

Cloud-based manufacturing is a rising technology which can contribute significantly to the realisation of Industry 4.0 that enables modularization and service-orientation in the context of manufacturing, in which systems orchestration and sharing of services and components are important considerations (Wang et al. 2014; Thames and Schaefer 2016; Moghaddam and Nof 2017). Mourtzis and Vlachou (2016) have discussed cloud-based CPS for manufacturing systems. Cloud manufacturing, similar to cloud computing, uses a network of resources in a highly distributed way. Manufacturing-as-a-Service (MaaS) has been gaining attraction in the manufacturing industry. Cloud design allows anyone to upload and share designs with others. Local Motors, an American motor vehicle-manufacturing company, focused on low-volume production of open-source motor vehicle designs using multiple micro-factories. Their designs are co-created by designers, engineers, fabricators and enthusiasts in its virtual community. This is an example of using a cloud design. Cloud design and manufacturing is considered to be the next paradigm in manufacturing, and extensive research is being conducted on its significance in Industry 4.0 (Branger and Pang 2015).

A modern enterprise's operation involves numerous decision-making activities, requiring a large amount of information and intensive computation. At one point, manufacturing enterprises required multiple computing resources such as servers for databases and decision-making units. This caused inefficient data exchange and sharing, low productivity and less optimal utilisation of manufacturing resources. Cloud computing provides an effective solution to such problems. All data can be stored in private or public cloud servers, and in this way, complex decision-making tasks can be supported by cloud computing.

3.3 *Cyber-physical systems*

In the past decades, cyber and physical systems are becoming increasingly interconnected (Nayak et al. 2016). CPS is the core foundation of Industry 4.0 (Varghese and Tandur 2014; Lee, Bagheri, and Kao 2015; De Silva and De Silva 2016; Zhou, Liu, and Liang 2016; Mladineo, Veza, and Gjeldum 2017). In CPS, physical and software components are deeply intertwined, each operating on different spatial and temporal scales and interacting with each other in a myriad of ways that change with context (Wikipedia 2017a; Chen 2017a). CPS present a higher level of integration and coordination between physical and computational elements (Gürdür et al. 2016; Wikipedia 2017a). Predecessors of CPS can be found in industry areas as diverse as manufacturing, aerospace, automotive, chemical, energy, healthcare and transportation (Yin et al. 2016; Nuñez and Borsato 2017; Wikipedia 2017a; Chen 2017b). The US National Science Foundation (NSF) has identified CPS as a key area of research. Starting in late 2006, the NSF and other US federal agencies have sponsored research projects regarding CPS.

CPS are engineered systems that are built from, and depend upon the seamless integration of computational algorithms and physical components. Advances in CPS will enable capability, adaptability, scalability, resiliency, safety, security and usability that will far exceed the simple embedded systems of today (NSF 2017), as Figure 4 shows. New smart CPS will drive innovations in sectors such as manufacturing, energy, transportation, agriculture, automation and healthcare.

> Traditional analysis tools are unable to cope with the full complexity of CPS or adequately predict system behavior. For example, as the Internet of Things (IoT) scales to billions of connected devices – with the capacity to sense, control, and otherwise interact with the a human and the physical world – the requirements for dependability, security, safety, and privacy grow

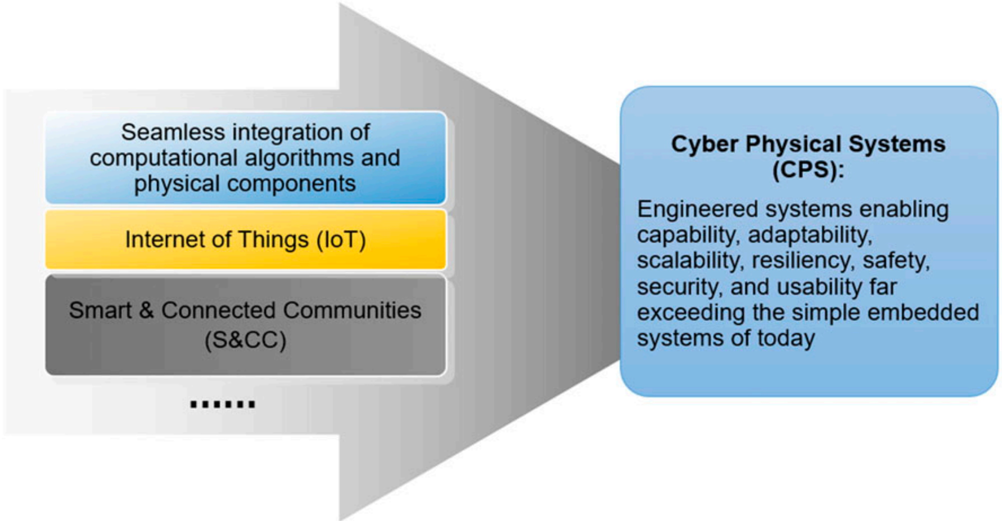

Figure 4. CPS.

> immensely. One barrier to progress is the lack of appropriate science and technology to conceptualize and design for the deep interdependencies among engineered systems and the natural world. The challenges and opportunities for CPS are thus significant and far-reaching. New relationships between the cyber and physical components require new architectural models that redefine form and function. They integrate the continuous and discrete, compounded by the uncertainty of open environments. Traditional real-time performance guarantees are insufficient for CPS when systems are large and spatially, temporally, or hierarchically distributed in configurations that may rapidly change. With the greater autonomy and cooperation possible with CPS, greater assurances of safety, security, scalability, and reliability are demanded, placing a high premium on open interfaces, modularity, interoperability, and verification. (NSF 2017)

According to the NSF, we have seen a convergence of CPS technologies and research thrusts that underpin the IoT and Smart & Connected Communities (S&CC). These domains offer new and exciting challenges for foundational research and provide opportunities for maturation at multiple time horizons (NSF 2017) (see Figure 4).

In Industry 4.0, CPS is expected to provide the basis for the creation of Industrial IoT, which combines with advanced ICT to make Industry 4.0 possible. CPS connects virtual space with physical reality by integrating computing, communication, and storage capabilities; furthermore, it can be real-time, efficient, reliable, and secure (Cheng et al. 2016). CPS is considered to be an Industry 4.0 enabling technology that will merge the virtual and the physical worlds (Saldivar et al. 2015), making the boundaries between these two worlds disappear. Industry 4.0 manufacturing systems will be collaborative systems involving various communicating agents including physical agents, software agents, and human agents. This will result in a fusion of both technical and business processes leading the way to a new industrial age, resulting in the smart factory (GTAI 2014). CPS can improve resource productivity and efficiency and enable more flexible models of work organisation (GTAI 2014). Industry 4.0 applies CPS to build Cyber-Physical Production Systems (CPPS), which connect the physical world with the virtual world, enabling the equipment in smart factories to become increasingly intelligent, which eventually will enable smart production (Zhou, Liu, and Zhou 2015). CPPS made up of smart machines, production facilities and logistics systems are expected to allow ICT-based higher level integration for vertically integrated and networked manufacturing (GTAI 2014).

The essence of Industry 4.0 is applying CPS to realise smart factories (Kusiak 2017). In other words, the smart factory is made possible by CPS-based production systems. CPS can play a major role in smart factory manufacturing and production processes. This provides significant real-time, resource, and cost advantages in comparison with classic production systems (GTAI 2014). In Industry 4.0, smart factory and intelligent production are the two major components. A smart factory focuses on intelligent manufacturing systems and processes, and implementation of networked, distributed production facilities (Zhou, Liu, and Zhou 2015; Ivanov et al. 2016). In a smart factory, things-to-things interactions are considered.

In Industry 4.0, complex engineering problems have to be jointly solved by multi-disciplinary teams with multitudinous computational software and physical systems. The efficiency and effectiveness of solving complex engineering problems largely depend on strategic collaboration (Schuh et al. 2014), seamless integration of disparate CPS, and integration of heterogeneous data. Wang (2016) presents a multidisciplinary design and analysis (MDA) environment in conjunction with its application to aircraft flight dynamics analyses. The MDA infrastructure has built a cybernetic platform that integrates structure analysis and flow computation systems with wind tunnel experiment systems; moreover, this reconciles and interoperates diverse data sources generated by the CPS.

In one application, for example, an automotive manufacturer employed cognitive technologies to optimise the configuration of its production line to balance the workload between stations, use labour more efficiently, and increase the rate of production while also adhering to its design for manufacturing (DFM) practices. The application enabled the manufacturer to reduce operating costs and capital investments by about 10%. In another application, an automobile manufacturer used cognitive planning tools to optimise its use of available plant capacity to bring a new model of cars into production. The application enabled the manufacturer to reduce operating costs and capital investments by about 10%. In yet another application, a semiconductor manufacturer was able to reduce cycle time by 15% by reducing equipment idle wait times, thus increasing throughput and asset utilisation (IBM 2017).

3.4 *Industrial integration, enterprise architecture and enterprise application integration*

In the first half of the first decade of 2000, the impact of ICT on industry went beyond the traditional paradigm. It affects industrial processes and production in an unprecedented way (Xu et al. 2016). It has become more and more clear that the emergence of Industrial Integration grew out from a new era of ICT, which occurred at the stage of the Third Industrial Revolution. Kaynak provided an example of industrial integration through the journey from industrial electronics to industrial informatics. According to Kaynak (2005),

> If we had a look at the industrial developments that took place in the 20th century, the first half could be said to be hardware dominated in the sense that the improvements in productivity and product quality were mostly due to improvements in 'the hardware.' The operational speed and the accuracy of the industrial machinery steadily increased, mostly due to the improvements in the precision of the mechanical parts. Along the same lines, the early second half could be said to be software dominated. It was the software used in microprocessor based control systems that enabled a production line to operate faster and more accurately. Even the improvements in industrial machinery (the hardware) were due to the possibilities offered by Computer-Aided Design and Manufacturing. The era of industrial electronics got started around this period, industrial automation in the form of mechanical controls and switches, slowly giving way to electronic controls and signal processing. The last few decades of the century, on the other hand, are characterized by the fusion of different technologies, the first example of which may be (going back almost to the start of the century) was electromechanics, then optoelectronics, followed by mechatronics, then telematics, then bioinformatics, and so on. As a result of this, the boundaries between industrial sectors and academic disciplines have eroded very rapidly. In the new millennium, it is very difficult to put clear boundaries between industrial sectors, between products and services, between producers and users, between IT, communications, media, consumer electronics and even between IT and non-IT industries. The area of industrial automation and control has had its share of the changes too.

Kaynak (2005) further wrote 'The area of industrial automation and control has had its share of the changes too. It is easy to see how dominant IT has become in industrial electronics if one considers the changes in time spent by an engineer in designing a controlled drive system:

- Before the 1960s: 80% for designing a control system with mechanical switches.
- After the 1960s: 80% for designing power electronics converters.
- After the 1980s: 80% for designing digital hardware and software.
- Currently: 90% for software and IT'

Presently, it is clear that the Fourth Industrial Revolution has been emerging from the current ongoing process of the Third Industrial Revolution, which is an industrial integration process, as new ICT is capable of integrating both new and classical industrial production processes. As organisations move past the hype surrounding digital transformation in Industry 4.0, they face the complex realities of implementation ranging from introducing new CPS and smart factories technologies and applications to adapting or replacing core enterprise architectures (EA), ICT infrastructures and processes. Colombo, Schleuter, and Kircher (2015) and Arnold, Kiel, and Voigt (2016) indicate that in the transition of traditional industrial ecosystems to Industry 4.0 will not only require new ICT but also new business models at intra- and inter-organisational levels to be developed. In Industry 4.0, the realisation of three integration formats horizontal integration, vertical integration, and end-to-end integration (Oliveira and Álvares 2016) require changes in enterprise architecture, ICT integration and processes (GTAI 2014).

In the current process of industrial integration, CPS represent a paradigm shift from existing business and market models, as revolutionary new applications, services and value chains will become available. Industrial sectors including the manufacturing, automotive, energy and others, will in turn be transformed by such new value chain models in the process of industrial integration (GTAI 2014). Researchers indicate that Industry 4.0 will stand for a new level of organisation (Albers et al. 2016). Industry 4.0 will reshape industrial organisations' enterprise architectures, leverage existing ICT infrastructures and business processes and create Industry 4.0 CPS capabilities as needed. Due to the arrival of Industry 4.0 and the profound changes to complex industrial ecosystems (Rennung, Luminosu, and Draghici 2016), there is the need to embrace new architectures and new business processes that will help an industrial organisation with the adaptation of existing enterprise architecture, ICT infrastructures, processes and relationships to support the transformation.

The Gartner Group describes the enterprise architecture (EA) change process as one that is creating, improving, and communicating the key requirements, principles and models that describe the enterprise's future state and enable its evolution. EAs are important because they can function as the blueprints used to understand and guide large and complex organisations. In the United States, Department of Defence (DoD) organisations are mandated by law to build and maintain EAs (Hoyland et al. 2014).

An enterprise architecture (EA) presents the structure of an enterprise and consists of the main enterprise components such as a company's goals, organisational structures, information infrastructure and business process. The performance of an enterprise, such as innovations generated within the company, the re-engineering of business processes, and the quality and timeliness of information flow, can be improved if the EA system faithfully represents the characteristics and the nature of the organisation (Xu 2011).

Integration, consolidation and coordinated applications have been identified as a critical issue in the Industry 4.0 environment. The boundaries of individual factories will most likely fade away. Factories in different industrial sectors and different geographical regions will be interconnected or integrated. Most probably, an enterprise will have some existing legacy systems that it intends to continue to use, and meanwhile, it will add a new set of applications to the operation. To address the integration of new and existing applications, an ICT solution, which is referred to as Enterprise Application Integration (EAI) (Yu and Madiraju 2015; Gorkhali and Xu 2016) can be applied. In order to integrate the new CPS-based digital capabilities with existing architectures, systems and processes, the coordination of various systems and applications greatly depends on EA, EI and EAI. Weber has pointed out that one of the important issues surrounding Industry 4.0 is the fact that existing equipment is not capable of communicating with newly deployed technology (Weber 2016). This obstacle can be overcome by Enterprise Application Integration (EAI) system, which is created with different methods and on different platforms, and aims at connecting the current and new system processes, providing a flexible and convenient process integration mechanism. The integration of enterprise applications includes the integration of heterogeneous data sources, processes, applications, platforms and standards. Through creating an integrative structure, EAI connects different systems and applications both intra-organizationally and inter-organizationally. By combining software, hardware, and standards, EAI makes sharing and exchanging data and information seamlessly possible (Xu 2011), which is required by Industry 4.0. A complete EAI offers functions such as process integration and information integration which will be introduced in 3.4.2 and 3.4.3.

3.4.1 *Service-oriented architecture (SOA)*

Service-oriented architecture (SOA) is a prevalent trend in integrating heterogeneous systems. It has received a great deal of attention from companies that are interested in implementing Industry 4.0. Industry 4.0 creates a cyber-physical manufacturing environment that enables the communication and interaction amongst all the players in the value-creation chain. In this sense, service-oriented architectures serve as an emerging paradigm for enterprises to coordinate seamlessly in the environment of heterogeneous information systems, enabling the timely sharing of information, and enhancing integration. Comparing with hierarchical enterprise architectures, SOA is an architecture for integrating platforms, protocol, and legacy systems and can be used to improve system flexibility and seamless transition of reconfiguration (Izza 2009). Some well-recognised advantages of service-oriented infrastructures and applications are simplicity, adaptability, scalability, flexibility, reliability and location independence (Petrasch and Hentschke 2016).

The functionality of SOA is an important feature to increase efficiency of new application development. Taking an architectural approach, SOA takes manufacturing applications and breaks them down into individual functions as services that allow the recursive aggregation of services into new processes and applications (Quartel 2009; Unger, Mietzner, and Leymann 2009; Xu 2011). Each of these existing services can be pieces of application functionality that represent a re-constructed task and can be re-used to create new applications.

Industry 4.0 can be benefited from applying the functionality of SOA because functionality enables manufacturing companies to create new customised applications to meet the diverse needs from customers. Services developed and maintained in one place can be made available to applications in other geographic locations in a cyber-physical environment (Xu 2011). Supply chain partners can integrate services in a remote location into their own functionality for manufacturing tasks. As such, SOA has been recognised as one of the key technologies that can enable globally integrated manufacturing systems (Theorin et al. 2017). SOA ensures access to industrial ecosystem's information for supply chain partners at different echelons of the value-creation chain, which creates a more flexible and responsive environment.

SOA can minimise the gap between EA analysis and ICT infrastructure redesign. It is also a crucial foundation for Business Process Management (BPM) in Industry 4.0 environment. BPM supports rapid orchestration and assembly of process services into larger, end-to-end processes, which is a major task in Industry 4.0. SOA, in conjunction with BPM, is expected to introduce promising technologies for developing Industry 4.0 environments. We may predict that the integration and co-evolution of SOA and BPM are on the horizon (Lorincz 2007).

3.4.2 *Business process management (BPM)*

All manufacturing organisations can be viewed as a business process that transforms inputs (that include material, labour hours, facility and equipment usage) to products or services to meet customer demands. Industry 4.0 introduces possibilities that may disrupt traditional manufacturing approaches that many manufacturing firms have implemented with their production planning and control methods (Moeuf et al. 2017). In a cyber-physical industrial ecosystem, business processes will be profoundly changed. The architecture of an enterprise will require novel business models (GTAI 2014).

Business Process Management (BPM) is particularly relevant to production and operations management (POM) because POM applies methods to analyse, measure, model, automate, optimise and improve manufacturing processes. In an Industry 4.0 ecosystem, business process management will aim at supporting an organisation's strategic goals, aligning resources within a company, between companies, or even across an entire supply chain. This integrated business process management approach will improve an organisation's overall performance, and enhance the efficiency, effectiveness and flexibility of an enterprise's daily operations (Wang, Xu, and Peng 2007; Xu et al. 2008; Hur, Katebi, and Taylor 2011; Li et al. 2014).

Modelling business and manufacturing processes is very important in an Industry 4.0 environment because production processes will be digitally supported using artificial intelligence, robots, machine learning, cloud computing, RFID and blockchain. BPM helps clarify the process of a new platform under the scope of Industry 4.0. In order to understand and optimise manufacturing processes, variability in a production process needs to be controlled at the each of the many processing steps (Chan, Dillon, and Kwong 2011). All of the process details in a manufacturing process related to the desired outputs of the process need to be collected, analysed and optimised (Xu 2011). The goal of Industry 4.0 initiative will be extended further than the horizontal and vertical integration within an industrial organisation (PWC 2016); it is to create a seamless integration of processes in smart cyber-physical factory (Zhou, Liu, and Zhou 2015; Ivanov et al. 2016).

Workflow management has been considered as an efficient way of monitoring, controlling, and optimising business processes with the support of ICT. The concept of workflow was initially developed to track process-related information and the status of each instance of the process as it moves through an organisation (van der Aalst 1998). Workflow management has been recognised as valuable measures that enable process management, process reengineering and eventually the automation of organisational business processes (Xu 2011). Increased process efficiency through improved information availability, process standardisation, task assignment on an automatic basis, and process monitoring using specific management tools are some useful features of Workflow Management System (WfMS).

The potential contribution of workflow management to an Industry 4.0 environment is to automatically track process-related information and make it available in the entire system for sourcing, production, inventory management, order management, demand sensing, quality control, and process reengineering. Interconnecting business processes across systems and organisations as in Industry 4.0 would provide obvious benefits, such as higher degrees of integration, facilitation of communication, higher throughput in a given time interval, and greater process transparency. Both intra-organisational and inter-organisational workflow architectures support Industry 4.0 as they focus on not only independent enterprises, but also the deployment of cohesive business processes over multiple enterprises.

Amongst the process modelling techniques, most of them have shown the capability of using graphical representation and formal semantics (Xu et al. 2012; Xu and Viriyasitavat 2014; Viriyasitavat 2016; Viriyasitavat and Martin 2017) to model workflows in an intra-organisational context (Schulz and Orlowska 2004; Xu 2011). Currently, there is an urgent demand for translation between various models so that different workflow management systems can operate with each other in the Industry 4.0 environment. This is an interesting research topic that has not received much attention to this point. Further study could lead to powerful methods enabling integrating heterogeneous models into a common framework in the Industry 4.0 environment.

3.4.3 *Information integration and interoperability*

Industries have experienced many changes over the past decade; in particular, a decade in which the key change is that industries are becoming more inter-connected in the process of industrial integration (Xu 2007, 2016; Lu 2016; Xu et al. 2016; Khan and Khan 2017b). In recent years, the concept of integration as a core competency of digital transformation has been widely recognised (Chen 2016; Fleming 2016; Vogel-Heuser and Hess 2016). With regards to competency in integration, Subrahmanian and Rachuri (2008) reported numerous incompatibilities in information exchange and coordination within industries; for instance, the delays that occurred in Airbus 380 and Boeing 787 manufacturing and assembling are examples of problems of this nature (Subrahmanian and Rachuri 2008). Regli (2007) indicated in 2007 that the information integration within or across industrial sectors is still a dream. Regli and other researchers have also indicated the key issue in this aspect is 'the apparent lack of fundamental progress in areas of information integration' (Regli 2007).

One of the five main features of Industry 4.0 is integration (Cheng et al. 2016). In addition, the core idea behind interoperability is also integration, which also is the key point of IoT and CPS (Qin, Liu, and Grosvenor 2016). In Industry 4.0, there are three major types of integration: horizontal integration, vertical integration and end-to-end integration (Qin, Liu, and Grosvenor 2016). Liao et al. (2017) have specified these three types of integrations in Industry 4.0 as (1) Horizontal Integration: integration of the various IT systems used in the different stages of the manufacturing and business planning processes within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks) (Kusiak 2017); (2) Vertical Integration: integration of the various IT systems at the different hierarchical levels (e.g. actuator and sensor level, manufacturing and execution level, production management level, and corporate planning levels) to deliver an end-to-end solution; and (3) End-to-End Digital Integration: integration throughout the engineering process so that the digital and real worlds are integrated across a product's entire value chain and across different companies, whilst also incorporating customer requirements. Industry 4.0 is expected to achieve all three major integrations as described above, plus hardware integration, software integration, and data and information integration. Efficient real-time integration of data in Industry 4.0 production processes needs to be ensured, as the support of automation in Industry 4.0 requires such integration. The ability to use integration effectively to handle end-to-end coordination (emphasised by Industry 4.0) of activities across the industrial ecosystems within the Industry 4.0 initiative will provide the necessary technological support for realising the goals related to the aforementioned initiative. The new trend is that businesses of all sizes that involve with Industry 4.0 will need to share and exchange data. Industry 4.0 systems must be inter-connected, and the applications composing the information systems of enterprises increasingly must seek to work together. The demand for integration has been increasing, as a consequence of the newly proposed Industry 4.0, and can be made possible due to the advancement of ICT including industrial information integration (Xu 2015, 2016).

In Industry 4.0, the concept of interoperability includes the ability of the Internet of Services, humans and organisations to connect and communicate via IoT and CPS, as well as the interoperability of the systems accommodating data flows (Shi et al. 2012; Zhou et al. 2014; Colombo, Schleuter, and Kircher 2015; Kusiak 2017). Recent advances in industrial information integration offer powerful approaches for effective and efficient information integration, a basic requirement for the success of Industry 4.0 (Branger and Pang 2015; Seetha Lakshmi et al. 2017). The current industrial systems may be limited by the sophistication of the relevant technologies or by the lack of techniques, and this is crucial because the successful execution of Industry 4.0 relies upon more sophisticated integration than what is currently available.

4. Research challenges and directions

It is broadly accepted that the Industry 4.0 technologies and applications are still in their infancy (Roblek, Mesko, and Krapez 2016). The potential economic benefits of industry 4.0 may be offset with a few major challenges. Some key challenges have to do with scientific, technological, and societal issues (Zhou, Liu, and Zhou 2015) including the challenges on technical aspects of technology, security and privacy, and standardisation. Efforts are needed to address these challenges.

4.1 *Technical challenges*

Although research efforts have been devoted to advance Industry 4.0 technologies, there are still technical challenges:

(1) For many manufacturing companies, the existing ICT infrastructures are not entirely ready to support the digital transformation to Industry 4.0 which aims at horizontal integration, vertical integration and end-to-end integration (Deloitte 2015; Oliveira and Álvares 2016; Liao et al. 2017). As mentioned in 3.4, Colombo, Schleuter, and Kircher (2015) and Arnold, Kiel, and Voigt (2016) suggest that in the transition of traditional industrial environment to the Industry 4.0 ecosystems, new ICT as well as new business models at both intra-organisational and inter-organisational levels need to be developed.

(2) Scalability is a big challenge in an Industry 4.0 environment. As more and more physical objects are connected to the manufacturing network, scalability issues arise. Given that manufacturing networks may be used for a wider variety of large volume transactional data and information at a high speed, the number of things will grow exponentially larger (Bi and Cochran 2014; Li, Li, and Zhao 2014; Li et al. 2014).

(3) Data science and data analytics will play an important role in the Industry 4.0 environment. With a huge number of things connected to the Internet, a massive amount of real-time data will be automatically produced by connected things (Wang et al. 2013). Unprocessed data may not provide meaningful value to decision-making in a cyber-physical production network unless these data are effectively analysed and utilised for manufacturing decisions (Li and Xu 2001). In order to analyse massive amounts of data generated from both IoT applications and existing ICT systems, data science and data analytics techniques should be developed and employed (Cheng et al. 2017). Building practical applications in which big data from a verity of heterogeneous sources are integrated can be a challenging task.

(4) IoT-related technical challenges. IoT is a very complicated heterogeneous network, which includes the connection between various types of networks through various communication technologies (Xu, He, and Li 2014). As of today, there is not a commonly accepted platform that can accommodate the variety of communication technologies and applications in the network (Miorandi et al. 2012; Xiao et al. 2014). Frequent delays in data transformation and other communication issues will rise when a huge amount of data concurrently transmit across the network (Xu, He, and Li 2014). Allowing data gathered by a large number of devices to be processed efficiently and smoothly within IoT networks is a challenging task. Much more research is needed to tackle the obstacles of managing connected things to facilitate the collaboration between different entities in a common platform. Managing devices addressing, identification and optimisation at the architectural and protocol levels also deserve a decent amount of research effort (Bandyopadhyay and Sen 2011; Xu, He, and Li 2014). Integrating IoT with existing ICT systems or legacy systems to form a unified information infrastructure is required since IoT has often been developed based on a traditional ICT environment while also being affected by everything connected to the network.

4.2 *Standardisation*

Industry 4.0 has the potential of becoming the global language of production (GTAI 2014). Each process used in an Industry 4.0 system integrates existing and proven technologies with new technologies and applications to address manufacturing problems. As such, the introduction of a uniform industry standard is especially important (GTAI 2014; Kusiak 2017). A global level of effort is required to develop a standardisation process to ensure successful implementation of the strategic vision of Industry 4.0. International cooperation efforts and a system-level perspective are needed to address the Industry 4.0-related standardisation (Lin et al. 2013; Wang et al. 2018). For example, a set of uniform technical standards are required so that a network that connects different factories and companies can be realised (Zhou, Liu, and Zhou 2015). Currently, the standardisation of Industry 4.0 is off a good start. Researchers have addressed the standardisation issues concerning technologies such as IoT and CPS that support Industry 4.0 implementation.

Some standardisation efforts have been reported. For example, the Reference Architecture Model for Industry 4.0 (RAMI 4.0), a key standard for Industry 4.0, has been introduced by the German Electrical and Electronic Manufacturers' Association (Rojko 2017). RAMI 4.0 introduces a three-dimensional coordinate system that describes all crucial components of Industry 4.0. Within this system, complex and complicated interrelations can be decomposed into subsystems, clusters, or modules (VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik 2015; Gøtze 2016). Another effort of developing standardisation for Industry 4.0 is the introduction of The Industrial Internet Reference Architecture (IIRA). IIRA is a standards-based open architecture defined by the Industrial Internet Consortium (IIC) (2017). The objective of IIRA is to create a capability to manage interoperability, map applicable technologies, and guide technology and standards development. The IIRA supports several aspects related to the standardisation. It includes (1) a diverse set of system types; (2) many configurations; (3) connections in a diverse set of ways; and (4) case contexts in many types of industries, sectors, and use. Recently version 1.8 of the IIRA was released. This new version incorporated emerging Industrial Internet of Things (IIoT) technologies, concepts, and applications.

The rapid growth and evolution of IoT make standardisation more challenging (Xu, He, and Li 2014). Nevertheless, standardisation plays an important role in the further development and the spread of IoT. Standardisation in IoT mainly aims at improving the interoperability of different applications/systems (Xu, He, and Li 2014). Standardisation efforts are urgently needed to ensure devices and applications from different countries to be able to exchange information (Miorandi et al. 2012; Xu, He, and Li 2014). Various standards such as communication standards, identification standards and security standards used in IoT might be the major drivers for the spread of IoT technologies. Specific issues in IoT standardisation include interoperability issue (including semantic interoperability), radio access level issues and security and privacy issues (Xu, He, and Li 2014; Curi de Moura Leite et al. 2017; Li and Xu 2017).

4.3 *Information security and privacy protection*

As the physical world and virtual space become integrated, security issues will become increasingly serious in the Industry 4.0 ecosystem (Kusiak 2017; Moeuf et al. 2017). Industry 4.0 demands an increasing degree of information security and privacy protection. There are existing technologies that are available for protecting organisational information security, but they may not be sufficient for industrial applications that have their own safety and security rules and requirements.

To ensure the use of new IoT technologies and services, information security and data privacy protection are critical aspects that the future research should consider. The difficult issues in IoT security embeds in its deployment, mobility, and complexity (Li and Xu 2017). When existing encryption technologies borrowed from the WSNs and other networks are employed in building IoT, they must be carefully reviewed and analysed to ensure security (Xu, He, and Li 2014). Tremendous amount of personal and private information would be automatically collected when IoT is applied. Therefore, protecting privacy in the IoT environment becomes a more serious issue than that of the traditional ICT environment because the number of attack vectors on IoT entities is much larger. For example, a health monitor collects patient's heart rates and blood pressures, and then transmits them directly to the doctor's office over the Internet. The patient data could be compromised due to cyber-crime (Li, Xu, et al. 2012; Yin, Fan, and Xu 2012; Jiang et al. 2014; Xu, He, and Li 2014; Yan et al. 2015; Yin et al. 2016). Another example is that a food manufacturer uses a bio-sensor to monitor temperature and bacterial composition of food kept in the refrigerator. Food deterioration data are digitally sent back to the food company. If such data is hacked by cyber attackers, the company's reputation could be ruined (Miorandi et al. 2012; Xu, He, and Li 2014). Since cyber security is an emerging technological issue, some definitions of IoT privacy and legal interpretations are still vague. Although the existing network security technologies provide a basis for privacy and security in the IoT networks as well as Industry 4.0 system, more work needs to be done on reliable security protection mechanism for Industry 4.0 needs.

4.4 *Research trends*

The development of Industry 4.0 infrastructures will likely follow an incremental approach in growing from the existing technologies. International collaboration efforts and a system-level perspective are most desirable to address the Industry 4.0-related challenges (NSF 2017). Several research opportunities are identified and presented below.

(1) Integration of CPS. The integration of CPS includes integrating heterogeneous components, methods, and tools. The challenge includes designing interfaces to support heterogeneous components and the adaptive integration of components (Zhou, Liu, and Zhou 2015). More research should be done to investigate the integration of cyber and physical systems; this type of integration will result in complexities from the interactions amongst cyber systems and the uncertain dynamic behaviour of physical systems (Nayak et al. 2016).
(2) Verification and testing of CPS. Rigorous verification and testing of CPS are critical in the Industry 4.0 system because the integration of heterogeneous components can make the CPS complex. Developing uniform standards and specifications for verification and testing of CPS is an urgent task (Zhou, Liu, and Zhou 2015).
(3) Blockchain. World Economic Forum predicts that by 2027 10% of global GDP will be stored on blockchain technology (World Economic Forum 2015). In recent years, the interest to study the role to be played by blockchain in the manufacturing sector has been increasing. Some companies have started integrating blockchain concept into manufacturing practices. Potential applications of blackchain in Industry 4.0 include promoting resilience, scalability, security and autonomy, as well as the usage of blockchain to timestamp sensor data (Joshi 2017).

(4) Smart devices. An Industry 4.0 manufacturing environment is intelligent which requires more advanced smart digital devices (Zhou, Liu, and Zhou 2015). Industry 4.0 utilises artificial intelligence techniques and IoT to create intelligent things or smart objects. Arsénio et al. (2014) propose to create the Internet of Intelligent Things by bringing artificial intelligence into things and communication networks (Xu, He, and Li 2014). Researchers have projected that future IoT systems would have characteristics such as self-configuration, self-optimisation, self-protection and self-healing (Kephart and Chess 2003; Kortuem et al. 2010; Xu, He, and Li 2014). Smart objects will become more intelligent (Ding et al. 2013) and context-aware with larger memory, processing, and reasoning capabilities (Xu, He, and Li 2014).

(5) Resilient smart factory. Resilience is a concept in systems science and has been used as an attribute of a complex system (Lin et al. 2013). Industrial information integration has paid increasing attention to resilience as a system property (Xu 2015). A resilient smart factory would have systems that are tolerant to disruptions (GTAI 2014). In Industry 4.0, there are often high data flow rates and intensive processing requirements. As such, the system can experience insufficient system resources for processing to maintain high reliability. Smart factories are introduced to provide the reliability needed and are expected to be as resilient. Although achieving resilience in Industry 4.0 is challenging, efforts are needed to be directed to the interdisciplinary research that contributes to the development of a resilient industrial ecosystem. New technologies such as blackchain are expected to contribute to Industry 4.0 resilience.

(6) What does Industry 4.0 mean for existing ERP, EIS or ES technologies? ERP (Enterprise Resource Planning) are also called Enterprise Information Systems (EIS) or Enterprise Systems (ES) in recent decades (Feng et al. 2003; Wang et al. 2005; Xu 2007; Li et al. 2008; Li, Markowski, et al. 2008; Li, Markowski, et al., 2008; Li, Xu, et al. 2008; Xu 2011; Li, Ge, et al. 2012; Niu, Xu, and Bi 2013; Romero and Vernadat 2016; Nikander 2017). According to GTAI (2014), Industry 4.0 has sparked a discussion on whether ERP, EIS or ES will establish themselves as the dominant software systems in Industry 4.0. Although GTAI study (2014) has not given a clear cut answer on the matter, it is recognised that as interdisciplinary integration is the essence of Industry 4.0; and ERP, EIS or ES will have to address new challenges from Industry 4.0. According to a related study published in 2014, the authors have indicated that IoT and CPS related technologies have made a large impact on new ICT and future ERP, EIS or ES. In this study, it was predicted that new generation of ERP, EIS or ES will emerge from new ICT with the capacity of CPS (Xu, He, and Li 2014).

(7) Industry 4.0's other impacts. The arrival of Industry 4.0 will affect the style of work, transforming the traditional work-as-survival to work-for-life, to a final life-as-work. It will free up more time for people to pursue their interests, which in turn enables more diverse and flexible career paths and will allow people to keep working and remain productive longer (Branger and Pang 2015).

5. Summary

Industry 4.0 proposes the adoption of advanced ICT in manufacturing to enhance manufacturing efficiency and competency. The emergence of interest in Industry 4.0 has increased in recent years due to the belief that the current Industry 4.0 movement is marking a major turning point in history (Colombo, Schleuter, and Kircher 2015). Industry 4.0 is no longer a 'future trend'. For many enterprises, it is now at the heart of their strategic and research agenda (PWC 2016). GE and Siemens are rushing to solidify themselves as Industry 4.0 platform providers (PWC 2016). A number of companies in Germany are already developing and implementing Industry 4.0 for use. According to GTAI (2014), Industry 4.0 solutions are being developed in 45 different projects with a budget of around 100 million Euros. As Industry 4.0 is also of relevance to small and medium-sized enterprises (SMEs), Germany has set up a 5 million Euro technology transfer project specifically for SMEs to pass on Industry 4.0 solutions. However, many Industry 4.0 implementations are not currently employing the advanced and new technologies developed under the umbrella of Industry 4.0. Although some technologies and applications introduced in this paper are not being fully utilised in Industry 4.0, they are expected to have enormous potential in playing a major role in the near future. Successful Industry 4.0 relies upon more sophisticated technologies than those that are available now. Technologies will act as an enabler in Industry 4.0 for tomorrow's more effective and competitive industrial ecosystems. Currently, efforts focusing on blending the proposed capabilities of the Industry 4.0 and emerging technologies are needed. With this blending, Industry 4.0 will be able to harness the power of current and emerging technologies to dramatically improve the complex industrial ecosystems through adopting new technologies.

Increasing the quality of Industry 4.0 can be accomplished with proper integration of the existing and/or new technologies. With more advanced technologies such as CPS and industrial information integration, the overall quality of

Industry 4.0 will improve as the essence of Industry 4.0 is interdisciplinary or transdisciplinary integration, including industrial information integration.

There are still many challenges and issues that need to be resolved in order for Industry 4.0 to become more applicable. Designing Industry 4.0 systems involves complexity, which mainly stems from the high dimensionality and complexity. In recent years, there have been significant developments in this newly emerging technology, as well as actual and potential applications to various industrial sectors. However, the development of advanced methodologies, especially formal methods and systems approaches, have to be synced with the rapid technological developments (NSF 2017). As indicated by Weber (2016), Industry 4.0 is about the application of advanced technologies to manufacturing as a 'whole' in a systems perspectives. As indicated by US National Science Foundation, 'Despite significant inroads into CPS technology in recent years, we do not yet have a mature science to support systems engineering of high-confidence CPS, and the consequences are profound' (NSF 2017). NSF also indicated that the goal of the research direction of CPS is to develop the core systems science (Lin et al. 2013) needed to engineer complex cyber-physical systems that people can use, interact with, and depend upon (NSF 2017). Even for the designing of manufacturing systems, there exists a gap between the level of complexity inherent in manufacturing systems and the rich set of formal methods that could potentially contribute to the design of advanced Industry 4.0 manufacturing systems (Campos 2010). Despite advancements in the field of Industry 4.0, both in academia and industry, significant challenges still remain. They need to be dealt with in order to fully realise the potential of this fourth industrial revolution. Industry 4.0 will continue to embrace cutting-edge technology and techniques, and will open up new applications that will impact industrial sectors and tomorrow's complex industrial ecosystems. Advanced ICT can and will contribute to the success of Industry 4.0.

This paper reviews the recent research on Industry 4.0 from the industrial perspective. We first introduce the background of Industry 4.0 and then discuss the fundamental technologies that might be used in Industry 4.0. Next, we introduce some current research on the industrial applications of Industry 4.0. Afterwards, we analysed the research challenges and future trends associated with Industry 4.0. Different from other Industry 4.0 papers, a main contribution of this review paper is that it focuses on industrial applications and highlights the challenges and possible research opportunities for future industrial researchers.

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