

INTERNET OF THINGS ENABLED MANUFACTURING: A REVIEW

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ABSTRACT

Internet of Things (IoT) plays an important role in the manufacturing sector, allowing objects to be sensed and/or controlled remotely across existing network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems, and therefore resulting in improved efficiency, accuracy and economic benefit in addition to reduced human intervention. With the world-wide spread of Industry 4.0, IoT-enabled manufacturing is now one of the key supports to smart factory, intelligent automation, and real-time adaptive decision-makings. This paper comprehensively reviews related technologies and world-wide movements so that insights and lessons could be useful for academia and practitioners when contemplating IoT technologies for upgrading and transforming traditional manufacturing into an Industry 4.0 future.

Keywords: Internet of Things, Cyber-physical Systems, Manufacturing, Industry 4.0, Review.

1. INTRODUCTION

Manufacturing, as one of the backbones for a country or district, is on the cusp of a revolution since advanced technologies are making typical manufacturing systems smarter and smarter. Smart factory, regarded as an essence of Industry 4.0, could be enabled by Internet of Things (IoT), cyber-physical systems (CPS), and cloud computing (Lee, Bagheri et al. 2015; Trappey, Trappey et al. 2016). IoT-enabled manufacturing refers to an advanced principle where typical production resources are converted into smart manufacturing objects (SMOs) which are able

to sense, interconnect, and interact with each other to intelligently carry out manufacturing logics (Zhong, Dai et al. 2013). It plays a critical role in smart factory due to its ability to create modular structured components which are equipped with smart decision-making capability. In modern manufacturing, the potential for IoT to improve productivity and automation in the production process is vast. It was claimed that IoT has set in motion the idea of Industry 4.0 which is a new wave of changes decentralizing production control and triggering a paradigm shift in manufacturing field (Bi, Xu et al. 2014). When manufacturing resources becoming more and more interlinked, IoT-enabled manufacturing can reduce work-in-progress (WIP) items, increase productivity, and improve product quality.

Most of the companies care about the physical flows which are created by the manufacturing activities so as to add values for various materials in specific production sites such as shop floors or assembly lines. By making full use of IoT technology, such flows are synchronized with their information flows which are created by different kinds of digital devices deployed in the production environment (Dai, Zhong et al. 2012). Thus, physical SMOs will be inextricably linked to their information flows. For example, a piece of raw material *X* will tell us that “I am a key component for product *Y* which is ordered by customer *Z*.” Within the IoT-enabled manufacturing environments, thousands of SMOs create a digital world where the manufacturing processes are streamlined and automated, the production decision-makings are optimized and adapted, as well as the operational activities are revolutionized and visualized (Tao, Cheng et al. 2014, Zhong, Lan et al. 2016). Digitization in manufacturing field, based on IoT, could ultimately be used to reshape time and labour-consuming operational and manual tasks.

IoT has been kept in the eyes of industry practitioners and academia for decades. In order to comprehensively investigate the IoT-enabled manufacturing, this paper firstly attempt to review this topic by selecting 119 articles mainly from Scopus and Google Scholar databases.

Key technologies used in IoT-enabled manufacturing, for example IoT, Cyber-physical Systems (CPS), and Wireless Manufacturing are covered in Section 2. World-wide movement in this area is reviewed in Section 3 which highlights several major districts such as Europe, North American, Asian Pacific, etc. Section 4 gives a review of the applications of IoT-enabled manufacturing. Section 5 concludes this paper by highlighting some key observations/insights and suggestions.

2. KEY TECHNOLOGIES

This section aims to provide comprehensive background knowledge and context on the topic of IoT-enabled manufacturing. This will be further broken down into Internet of Things, Cyber Physical Systems, and Wireless Manufacturing, which are the most practical and influential technologies used in IoT-enabled manufacturing.

2.1. Internet of Things

The Internet of Things can be seen as transforming ordinary physical objects into smart objects by embedding smart sensors and an identity/personality. Li et al argued that the exact definition is still not agreed upon, but does agree that IoT can be treated as a superset of connecting devices uniquely identifiable (Li, Xu et al. 2015). They also presented a commonly accepted definition of IoT: “a dynamic global network infrastructure with self-configuring capability 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” (Xu, He et al. 2014). A few other definitions can be seen in (Haller, Karnouskos et al. 2008) and (Uckelmann, Harrison et al. 2011).

Regarding the architecture of the IoT, it is widely accepted that a Service Oriented Architecture (SOA) is best (Karnouskos, Guinard et al. 2009, Spiess, Karnouskos et al. 2009). The key benefits that SOA offer are how dynamic and adaptive it is, allowing reconfigurability and interoperability (Cannata, Gerosa et al. 2008, Guinard, Trifa et al. 2010). Additionally, it can treat a complex system as a set of well-defined simple objects or subsystems, allowing for reusability yet still maintaining individuality. This decoupling allows software and hardware components to be reused or upgraded separately which are similar to those of encapsulation and decoupling in object oriented programming. There are many approaches to the implementation and structure of this architecture, each with varying numbers of layers which are listed in Table 1.

Table 1. Implementation Approaches

Models	Key Characteristics	References
3 layer model	<ul style="list-style-type: none"> • Perception layer • Network layer • Application layer 	(Yun, Yuxin 2010, Jia, Feng et al. 2012, Domingo 2012).
4 layer models	<ul style="list-style-type: none"> • Sensing layer • Network layer • Service layer • Interface layer 	(Xu, He et al. 2014)
	<ul style="list-style-type: none"> • Resource layer • Perception layer • Network layer • Service layer 	(Tao, Zuo et al. 2014)
5 layer model	<ul style="list-style-type: none"> • Edge technology layer • Access gateway layer • Internet layer • Middleware layer • Application layer 	(Bandyopadhyay, Sen 2011)

Al-Fuqaha et al. (2015) also offered a look at many different architectures for IoT. The core of each of the models is similar: each contains a stage that utilizes smart objects and sensors to enable data generation about the state and environment of that object. Another stage is to

communicate the data between objects and to apply the knowledge behind the data. There exist many benefits of connecting manufacturing resources and machinery in the Internet of Things such as communication between resources and machines in and of itself allows for smoother automation, and a greater degree of tracking and control from a logistics point of view. But this ubiquitous connection of smart objects also enables the use of other paradigms, such as: Predictive Manufacturing (Gao, Wang et al. 2015), Cloud Manufacturing (CMfg) (Tao, Zhang et al. 2011, Tao, Cheng et al. 2014, Liu, Gao et al. 2011, (Xu 2012) and Big data analytics (Bin, Yuan et al. 2010, Chen, Deng et al. 2015 (Zhong, Newman et al. 2016). These paradigms bring manufacturing into a new era which is Industry 4.0 where physical processes could be monitored, a virtual world could be created, and decentralized decisions could be made (Lee, Bagheri et al. 2015, Zhong and Huang. 2014a, Liu and Xu 2017).

The Internet of Things is enabled by a few key technologies which have had extensive progressive in the last few years. The two main technologies are: Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSNs). RFID allows for unique, fast, and easy identification and tracking of objects without the need for line of sight. It consists of two parts: the tag and the reader. The tag is essentially a microchip attached to an antenna with a housing, and stores a unique Electronic Product Code (EPC), typically storing 64 – 96 bits, as per EPCglobal standards (Atzori, Iera et al. 2010). Tags can be split into two categories: passive and active RFID tags, referring to the power supply.

The RFID readers trigger the tags transmission by generating a signal to which the tags respond. Typically, passive RFID tags are the most commonly used in industry (Zhong, Li et al. 2013). RFID tags can be split into their operating frequency, low frequency (LF), high frequency (HF), and ultra-high frequency (UHF). (Dobkin, Wandinger 2005). Despite the benefits offered by RFID, such as low cost and small size, it also has constraints. It cannot provide detailed information about objects state, pin-point position, or environment. It more or

less provides unique identification and general positional area (Lu, Xu et al. 2016). It also has no processing power, so it cannot perform logic or filter/clean any data (Wang, Xu et al. 2014).

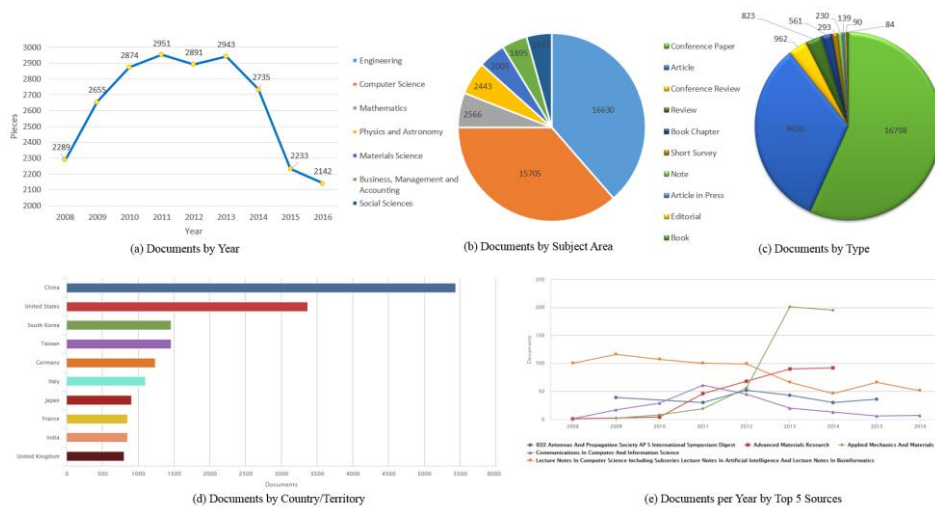


Figure 1. Statistics Analysis on RFID Research

RFID research has been had particular attention in recent years (Ahmad and Mohan 2014, Dimakopoulou, Pramadari et al. 2014, Leung, Cheung et al. 2014, Zhong, Huang et al. 2014a, Zhong, Huang et al. 2014b, Mejjajouli and Babiceanu 2015, Tesch, Berz et al. 2015, Zhong and Huang 2015a, Zhong, Huang et al. 2015b, Lu, Xu et al. 2016, Saab and Msheik 2016, Zhong, Lan et al. 2016). From Figure 1 (a), it could be observed that, from the year of 2008 to 2016, the total documents published are 23,713 with the average of 2635 documents per year. The major subject areas are shown in Figure 1 (b) from where Engineering and Computer Science take up 39% and 36% respectively. From Figure 1 (c), most of the documents are from conference papers and articles. RFID books are fewer (only 84) compared with other types such as notes and review. As shown in (d), the most active research countries/territories are China, United States, South Korea, Taiwan, and Germany where RFID research in terms of technologies and its applications are popular. (e) presents the top 5 sources about the keyword ‘RFID’. They are IEEE Antennas and Propagation Society APS International Symposium Digest, Advanced Materials Research, Applied Mechanics and Materials, Communications in Computer and Information Science, Lecture Notes in Computer Science including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics

Computer and Information Science, and Lecture Notes in Computer Science Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in bioinformatics, which mainly publish conference papers. Thus, it is implied that the RFID research and related topics are widely focused and commonly shared during conferences, symposiums and seminars.

2.2. Cyber-physical Systems

Cyber Physical Systems (CPS) refers to a mechanism or principle which uses computer software and physical components to build a deeply intertwined system so that Internet and its users could be seamlessly integrated. While, this term has been widely extended, thus, there are many definitions, some of which can be found in the Table 2.

Table 2. Definitions of CPS

Definition Descriptions	Reference
The integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.	(Lee 2008)
Systems that feature a tight integration between computation, communication, and control in their operation and interactions with the task environment in which they are deployed	(Wang 2010)
A cyber physical system integrates computing, communication and storage capabilities with monitoring and/or control of entities in the physical world, and must do so dependably, safely, securely, efficiently, and real-time.	(Sanislav, Miclea 2012)
Cyber physical systems are a next generation network connected collection of loosely coupled distributed cyber systems and physical systems monitored/controlled by user defined semantic laws	(Tan, Goddard et al. 2008)

Another defining aspect of CPSs are their characteristics. There is much literature attempting to characterize CPS, each with slight differences. Some examples can be found in (Shi, Wan et al. 2011, Wang, Törngren et al. 2015, Jazdi 2014). Lee, Bagheri et al (2015) summarized the characteristics as two main functional components: 1) the advanced connectivity that ensures real time data acquisition from the physical world and information

feedback from the cyber space; and 2) intelligent data management, analytics, and computational capability that constructs the cyber space. Despite the abundant definitions and characteristics, it can be hard to visualize. In the context of manufacturing, CPS can be the mirroring, networking, and controlling of physical systems via cyber space (Wang, Törngren et al. 2015). Each physical machine would have a cyber-twin that mimics the real physical machine, holding all information about the current and previous state of that physical machine, such as action, temperature, vibration, etc (Xu 2017). These cyber-twins would be able to communicate via a network, which could be the internet, but not necessarily. Additionally, the cyber-twin can control the physical machine, with feedback loops to ensure the convergence of states between the physical machine and cyber-twin. (Lee, Lapira et al. 2013, Lee, Bagheri et al. 2015).

The benefits of CPS are obvious from the literature. The interconnectedness of devices enables a greater degree of automation and tracking, but this connectedness and data generation can be exploited for further benefits (Zhong, Huang et al. 2015b). Key benefits can be summarized into 3 key categories: enhancing decision making, information sharing, and enabling other manufacturing concepts. Enhancing decision making can be seen as the utilization and visualization of Big Data Analytics, aiding human decision making, or enabling cyber decision making. Human decision can be aided through increased transparency via visualization of big data (Kretschmer, Pfouga et al. 2017). Transparency can be defined as “the ability of an organization to unravel and quantify uncertainties to determine an objective estimation of its manufacturing capability and readiness” (Lee, Lapira 2013). By knowing the manufacturing floors capability and capacity, management can make better decisions (Zhong, Huang et al. 2014b, Wang, Zhong et al. 2016). Cyber decision making can be seen as any resolutions made by the cyber hub as a result of analyzing the sensor data (Petnga and Austin 2016). These can include Prognostics and Health Management (PHM), Predictive

Manufacturing, and Resource flow and logistics optimization (Lee, Wu et al. 2014, Chen, Pan et al. 2017). PHM aims to analyze current and historic states of a machine to predict when maintenance is needed and useful remaining life. By avoiding unnecessary maintenance, costs can be reduced and uptime increased. Lee, Bagheri, and Kao (2015) outlined how to design a CPS for the purpose of PHM in Resource flow and logistics optimization aiming to optimize resource routes and the manufacturing process overall. The goal of predictive manufacturing is to determine what a user wants and start manufacturing it before an order is placed, or even knows what they want (Lee, Kao et al. 2014). This will reduce turnover time and increase satisfaction.

Enabling other manufacturing concepts includes some advanced concepts such as cloud manufacturing and Industry 4.0 which may use CPS for future applications or industry revolution. By enabling the widespread of adoption of these concepts, quality of the product will be increased since there will be less defects. CPS will generally increase efficiency of the manufacturing industry in terms of both inputs, such as resource, energy, and man hours, as well as outputs, such as the final product or service (Almada-Lobo 2016).

2.3. Wireless Manufacturing

Wireless Manufacturing can be thought of as “an umbrella term for manufacturing solutions enabled by wireless devices such as RFID and other types of wireless devices.” (Huang, Wright et al. 2009). In manufacturing environment, companies are looking hard for innovative approaches to leverage wireless manufacturing principles to enable more efficient operations so as to increase the customer satisfaction. Today, manufacturers are using great myriad of wireless equipment and applications such as automated production robots, unmanned logistics vehicles, and so on (Wu and Zhou 2007, Fantoni, Santochi et al. 2014, Lu, Xu et al. 2016). That brings significant benefits such as speeding the products and services delivery, increasing

the manufacturing efficiency and effectiveness, as well as improving the product quality and manufacturing systems' reliability (Zhong, Gong et al. 2016).

Under the era of Industry 4.0, smart sensors for manufacturing systems are essential so that remote management and control using wireless devices must be implemented in front-line production sites like shop floors. There are surrounded obstructions, interference, and obstacles in such areas. For example, RFID signals will be confined in a metal surrounded environment when using high frequency (Wang, Qu et al. 2012). Therefore, hybrid wireless solutions are needed to improve the communication reliability under complex situations. More reliable, consistent and intelligent wireless standards are adopted to wireless manufacturing so that they can automatically adapt to dynamics and interference (Huang, Zhang et al. 2008). For instance, a smart Gateway in a plug and play fashion was introduced following service-oriented architecture so as to manage various manufacturing objects in assembly workstations (Zhang, Qu et al. 2011). Taking full advantages of the multi-agents technology, the smart Gateway is able to define, configure and execute manufacturing operations on a real-time basis via wireless standards.

There are large number of applications using wireless manufacturing concepts. Table 3 lists several typical applications by highlighting the industry/company, aims, wireless standards, and future work.

Table 3. Typical applications of wireless manufacturing

References	Industry Company	Aims	Wireless	Future Work
(Virkkala 2007)	Agricultural industry, Finland	<ul style="list-style-type: none"> • Exam the innovation processes driven by wireless networks 	Nokia Networks	<ul style="list-style-type: none"> • Adopt more advanced ICT for the SMEs • Nokia Siemens Networks application
(Dai, Zhong et al. 2010)	Discrete Industry, China	<ul style="list-style-type: none"> • Design and develop a hardware platform for a paperless manufacturing 	RFID and 433MHz	<ul style="list-style-type: none"> • Advanced base station for better communication • More easy-to-deploy/configure system
(Peng 2008)	CNC system, China	<ul style="list-style-type: none"> • Design a wireless communication for CNC system 	2.4 G Bluetooth, ISM frequency channel	<ul style="list-style-type: none"> • Machining and manufacturing information integration • NC machine tools control
(Makris, Michalos et al. 2012)	Robotic assembly, Greece	<ul style="list-style-type: none"> • Enable the RFID based robotic assembly operations 	RFID and Ethernet	<ul style="list-style-type: none"> • A networking framework for communicating with robot controllers
(Rajesh, Gnanasekar et al. 2010)	Industrial application, India	<ul style="list-style-type: none"> • Propose an architecture to integrate the sensor network and Internet using Cloud technology 	Temperature Sensor Network, Cloud	<ul style="list-style-type: none"> • Distributed manufacturing with sensor network • Intelligence integration into the Internet
(Abdullah, Ismail et al. 2015)	Production Line Management, Malaysia	<ul style="list-style-type: none"> • Design an RFID-enabled production line management system 	RFID and ZigBee	<ul style="list-style-type: none"> • Hardware configuration • Software program improvement
(Barenji, Barenji et al. 2014)	FMS, Turkey	<ul style="list-style-type: none"> • Deploy an RFID-enabled distributed control system 	RFID and sensor network	<ul style="list-style-type: none"> • Distributed control systems structure • Improve definitions of WSN and DCS

(Dubey, Gunasekaran et al. 2017)	Framework implementation, India and US	<ul style="list-style-type: none"> Develop a conceptual framework for wireless manufacturing implementation 	RFID, Wi-Fi, 3G/4G	<ul style="list-style-type: none"> More impact factors on the implementation Technology integration analysis
(Holfeld, Wieruch et al. 2016)	Factory Automation, Australia & Germany	<ul style="list-style-type: none"> Design wireless communication for factory automation 	LTE and 5G	<ul style="list-style-type: none"> LTE's evolution for factory automation 5G for new business opportunities
(Schweer and Sahl 2017)	Digital industry, Germany	<ul style="list-style-type: none"> Analyze the benefits for Germany industry using wireless manufacturing 	Mobile network, Cloud computing	<ul style="list-style-type: none"> Centralized digital platforms Industry 4.0 technologies

From Table 3, it could be observed that wireless manufacturing has been widely applied in different industries and fields where different wireless technologies have been employed. In the early stage, wireless standards like 433MHz are mostly used in industrial applications due to its frequencies used in most nations worldwide. Recently, BlueTooth and Wi-Fi are more focused in the industrial implementation as the maturity of the emerging wireless technologies and the deceasing of their prices. Some cutting-edge wireless fashions like 5 G was introduced in some conceptual frameworks in industry for example Germany whose manufacturing systems are the leading applications in the world.

2.4. Comparison

As mentioned previously, there are many similarities between CPS and IoT which utilize ubiquitous sensing and computing, transforming ordinary objects into smart objects, with the vision of enabling communication between smart objects and a central hub. The key difference is that CPS does not necessarily need to be connected to the internet, the network it operates on can be a closed local network. This implies that CPS is broader in concept, and IoT is a CPS

specifically connected to the internet. (Wang, Törngren et al. 2015b, Jazdi 2014). However, due to the lack of a unified definition of CPS, it is argued that CPS belongs to the broader term of IoT (Wan, Chen et al. 2013). Other minor differences are that CPS specifically emphasizes the feedback from the cyber to the physical, i.e. the actuation and control, where as IoT does not. Additionally, it seems that from literature, IoT incorporates the use of RFID much more compared to CPS, and both heavily employ the use of WSNs. Despite the semantics, they all aim to increase connectivity between objects and devices and to make them smarter. By doing so it allows the use of advanced manufacturing strategies and technologies with the ultimate goal of Industry 4.0.

Large number of companies from different perspectives such as software and hardware are providing different technical support to enable the IoT solutions for manufacturing sector. Table 4 summarizes some top IoT companies which are able to support the IoT manufacturing from various categorizes. Table 4 presents the companies with their major expertise.

Table 4. Top IoT Companies for Manufacturing Industry

Featured	Company	Expertise
IoT Startups	Samsara	Samsara is designed for diverse environments from energy monitoring to asset utilization to vehicle tracking. Fully-wireless sensors are flexible and reconfigurable.
	Notion	Notion provides wireless home monitoring easily & effectively, regardless of location.
	Hologram IoT	The Cellular Connectivity Platform for IoT. Empowering makers, engineers & creators with cellular connectivity.
	Losant	IoT developer platform for building and visualizing real-time Internet of Things solutions with ease.
	Bastille	Bastille Networks is the first and only #CyberSecurity company to detect and mitigate threats affecting the Internet of Things #IoT.
	Helium	Deployable in minutes, Helium smart sensing solutions bring efficiency and innovation to your business through increased perception and insight.
	Filament	Filament provides turnkey wireless sensor networks for industrial customers that let you retrofit any existing machine, sensor, or device.

	Konux	With Konux technology, this company builds sensor solutions on the edge of the physical limits. We employ artificial intelligence to build gateways
Hardware	GainSpan	GainSpan is an industry leader in IoT Solutions, with a broad portfolio of state-of-the-art low-power Wi-Fi modules and chips, as well as plus drivers.
	Samsung ARTIK	Samsung ARTIK is the end-to-end, integrated IoT platform that transforms the process of building, launching, and managing IoT products.
	Particle	Particle is a prototype-to-production platform for developing an Internet of Things product.
	Libelium	Libelium is an Internet of Things, Smart Cities and M2M platform provider. It is also a Wireless Sensor Networks hardware manufacturer.
	Link Labs	Link Labs gives Connect applications with robust, secure M2M & IoT technology. It is a maker of Symphony Link - LoRa based long range wireless.
	Qualcomm IoT	Qualcomm IoT creates a world where devices, places and people become so inter-connected that daily life changes forever.
	Silicon	Silicon Labs makes silicon, software and solutions for a more connected world.
	Lantronix	Lantronix provides device networking products and offsite device control. Manage industrial IoT control systems or administer the entire data center.
Software	ProSyst	ProSyst is a software vendor, offering the middleware for the Internet of Things. Our roots are in the field of Java, OSGi and embedded software.
	Litbit	Litbit is the original creator and primary driver of the Apache Iota open source project. We use Iota as the core of our human+machine
	Antmicro LTD	Embedded software company, expert in OS porting and drivers, developing for industrial and IoT applications with a focus on prototyping.
	DGLogik, Inc.	DGLogik, Inc. offers an Internet of Everything Application Platform that allows users to Connect Various Data Sets, Build HTML5 Applications
Cloud Vendors	Ayla networks	Ayla's Internet Of Things (IoT) Enterprise Software Platform enables manufacturers and service providers to bring connected products to market.
	Xively	Xively by LogMeIn offers an award-winning Internet of Things product relationship management solution for enterprises building connected products.
	PTC	PTC provides technology solutions that transform how products are created and serviced, helping companies achieve product and service advantage.

	Arrayent	Arrayent Connect is the Internet of Things (IoT) platform of choice for trusted consumer brands, enabling them to implement connected products
	Buddy	Buddy Platform is a lightweight, fast and flexible platform for collecting and processing Internet of Things (IoT) data.
	SensorSuite Inc.	SensorSuite Inc. is a real-time machine intelligence platform. We reduce operational risks and improve the performance and efficiency of machines.
System Integrators	AMYX+	Amyx+ , an award-winning Internet of Things strategy & innovation lab, is working with international and
	TreeLine Interactive	TreeLine develops custom solutions for the Internet of Things (IoT).
	ThingLogix	It is a technology-enabled services firm focused on Internet of Things solutions. With our professional expertise and IoT technology.
	Flex	Flex is a leading sketch-to-scale™ solutions company that designs and builds intelligent products for a connected world.

3. WORLD-WIDE MOVEMENT

It should be noted that although IoT is a subcategory of CPS, IoT is a more widely used term within the public. Thus many sources refer to only IoT, however this does not discredit the relationship between IoT and CPS, and any insights gained regarding IoT movements can also be applied to CPS.

3.1. Europe

The GDP of the European Union is estimated to be \$16.3 trillion USD as of 2015, with approximately 24.4% of that attributed to industry. In this case, industry is defined as the value added through manufacturing, mining, construction, electricity, water, and gas (, World Bank Open Data2016). It is also estimated that 15.7% of the GDP is contributed by manufacturing alone. This means there is a large potential market for IoT/CPS enabled manufacturing, approximately a \$2.6 trillion USD market.

Many sources attempt to estimate the benefits IoT can bring to the EUs GDP. A.T. Kearney, a management consulting firm, estimated a 7% increase in GDP by 2025, with \$160 billion

Euros contributed by the manufacturing industry (Collignon, Vincent et al. 2016). A joint report by Fraunhofer Institute and Bitkom estimated that German GDP can be increased by a cumulative of \$267 billion Euros by 2025 through the introduction and utilization of Industrie 4.0 (Heng 2014). In this case, cumulative refers to the benefits of each year, accumulated. It is difficult to judge the accuracy of these estimates, but it is clear that these sources agree that IoT and CPS strategies can bring about significant increases in Europe's GDP, which can be viewed as an opportunity now to invest.

All EU funded projects are made public within the Community Research and Development Information Service (CORDIS) portal (CORDIS 2016). Within this, a search was made with the following search term: ('Internet of Things' OR 'Cyber Physical Systems' OR 'IoT' OR 'CPS' OR 'Wireless Manufacturing') AND (contenttype='project'). This searches for specifically projects that includes any of the key words mentioned. The results were then sorted by year and shown in Figure 2.

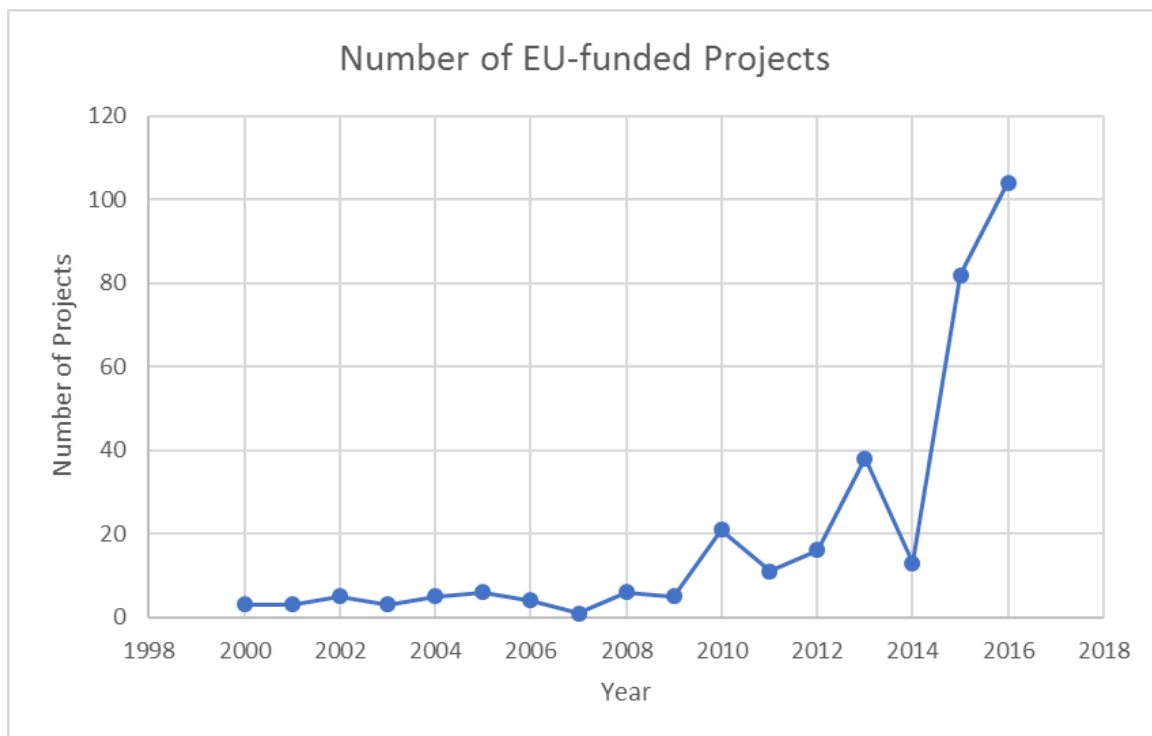


Figure 2. EU-funded Projects since 2000

It is clear that there is an increasing number of projects over time, which is an indicator that the area is still growing. There are several European initiatives that try to enable IoT and CPS, notably Horizon 2020 (H2020), which is part of the greater Europe 2020 strategy. H2020 is the largest EU research and innovation program to date, with \$80 billion Euros of funding from 2014 to 2020 (European Commission 2015). Within the scope of H2020 exists many initiatives relating to IoT. For example, an initiative specific to manufacturing is the ICT Innovation for Manufacturing SMEs (I4Ms) (SmartAnythingEverywhere 2015). The goal of this initiative is to “ensure that any industry in Europe, big or small, wherever situated, and in any sector, can fully benefit from the digital innovations to upgrade its products, improve its processes and adapt its business models to the digital change” (*I4Ms - Enhancing the digital transformation of the European manufacturing sector*. 2016). Another initiative relating to the overall implementation of IoT is the Digital Single Market (DSM), under the Europe 2020 strategy. This was adopted in 2015, and includes 16 initiatives. The main goals of DSM are to improve consumer and business access to digital goods and services, create the right environment for digital networks and innovative services to flourish, and maximizes the growth potential of the digital economy, all of which can culminate to \$415 billion Euros in additional growth (Digital Single Market). Despite being a general IoT initiative, it does however contribute to the R&D of IoT manufacturing. This clearly shows the governments belief in the benefits of CPS and IoT in manufacturing, and suggests it would be easy to gain government backing regarding related decisions.

As for current utilization, in 2011 it was reported that 3% of EU companies are using RFID. Of those companies, 56% use it for access control, 29% for supply chain, 25% for motorway tolls, 24% for security control, 21% for product control, and 15% for asset management (Van Kranenburg, Anzelmo et al. 2011). Note that the sum is over 100% because some companies can be included in more than one category, for example a company may use RFID for both

access control and supply chain management. Although this is not representative of manufacturing companies, it is clear that there is a lack of adoption of this technology with companies.

3.2. North American

As of 2015, North America's GDP is estimated at \$19.6 trillion USD, with 20.6% of that contributed by industry, and 12.3% from manufacturing alone. This means a \$2.4 trillion manufacturing market. The International Data Corporation (IDC) has predicted that by 2020, there will be 7.5 billion connected devices, compared to the 3.1 billion estimated for 2013. They have also predicted an IoT revenue of \$1922.1 billion USD in 2020, compared to the estimated \$667.9 billion USD in 2013 (Lund, Turner et al. 2014). A graph of the growth can be found in Figure 3.

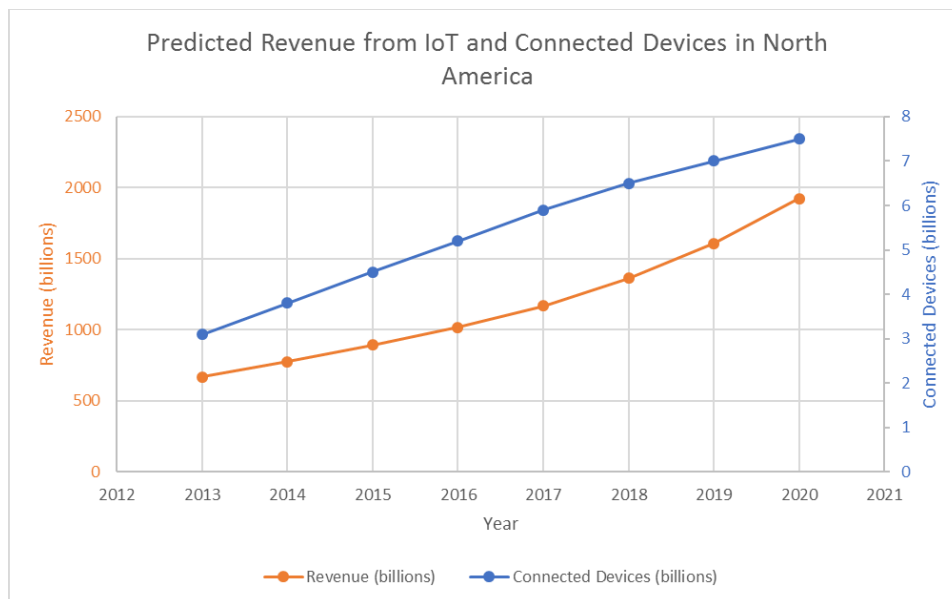


Figure 3. Growth of IoT Devices Connected in North America

Although there are differences in numbers between this and other sources, such as (MicroMarketMonitor 2016) and (Grand View Research 2016), the general trend is the same, a compounded annual growth of between 16% to 23% for the years up till 2020. Thus, there is

a general consensus in the market revenue growth of IoT in North America. Within the US, the majority of research and initiative funding is allocated by the National Science Foundation. Since the year 2000, they have been increasing the money allocated to the topics of CPS and IoT. Figure 4 depicts the number of projects that has received funds over the years, and the total amount award to those projects up to date.

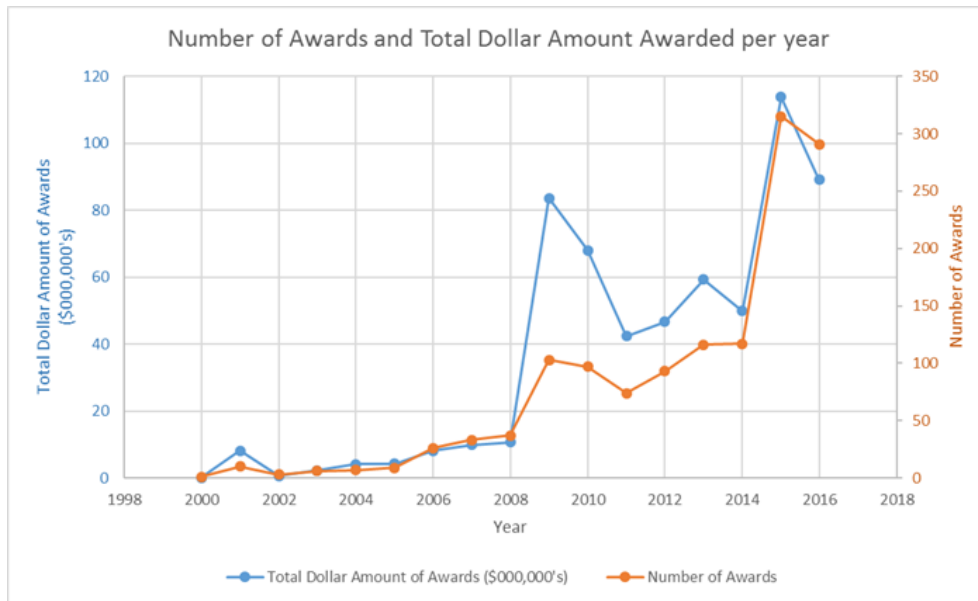


Figure 4. Awards in North American since 2000

An upward trend can be seen in both the amount of projects award funding and the amount of funding. However, it can also be seen that in the year of 2016, there is a decrease in the number of projects and the dollar amount funded to those projects. There are several possible explanations. First is related to the database of the NSF website. The data shown in the graph was retrieved near the end of 2016, however it may not have updated the database with some 2016 projects, leading to a lower number and dollar amount of projects and awards. The second is related to research itself. As a concept becomes a “hot topic”, the easier avenues of research are conducted first. Eventually it will lead to only leaving the more challenge issues, to which many researches may not want to participate in.

In a recent PwC report of 120 US manufacturing professionals, it was found that “thirty-five percent of manufacturers are currently collecting and using data by smart sensors to enhance manufacturing/operating processes; 17% plan to do so in the next 3 years, with another 24% with plans, but no timeline” (PwC 2015). Of the surveyed 120 companies, 34% believe it is extremely critical to adopt IoT strategies, whilst 60% believe it’s moderately or slightly crucial. Despite the small sample size and possible skewedness, a resounding majority believe IoT strategies are at least slightly crucial.

3.3. Asian Pacific

In 2013, the GDP of the combined East Asia and Pacific region was \$21 trillion USD, whilst industry made up 34.7%. Manufacturing made up 23.1% of the GDP alone, translating to a \$4.9 trillion USD manufacturing market. Revenue generated in the IoT market in the Asia Pacific region in 2015 was observed to be approximately \$439.6 billion USD, and is expected to grow to \$853.9 billion USD by 2020 (Statista 2016c). This suggests that the IoT market in this region will double in 5 years.

In China, a strategic plan called Made in China 2025 was proposed with the Guidance of the State Council on Promoting Internet + Action and 13th Five-year Plan on national Program for Science and Technology Innovation. Made in China 2025 has clear goals, guidance and road map for 30 years. There are nine missions and ten major development fields and give major programs (Li, Hou et al. 2017). In 2009 China has identified CPS as one of its major interest in the next stage of economic growth (Wang 2010). Beijing plans to invest 5 billion yuan (\$800 million) in the IoT industry by 2015. The Ministry of Information and Technology estimates China's IoT market will hit 500 billion yuan (\$80.3 billion) by 2015, then double to 1 trillion yuan (\$166 billion) by 2020. [<http://edition.cnn.com/2012/11/28/business/china-internet-of-things/>].

Recently, Japanese government initialized an Industry 4.0 plan which aims to create standards for technology to connect factories and to combine efforts to internationalize industrial standards from Japan. Mitsubishi, Fujitsu and Panasonic, some of the initiative's founding members, plan and act global this initiative to make a difference. Nissan Motor is also a member, which looks for areas of collaboration instead of understanding this as a competing model to Industry 4.0. "Intelligence Japan (I-Japan) strategy 2015" was also launched in 2009, to promote convenience of life and stimulate new vitality in this area. (Zhang, Zhu 2011).

3.4. Overall Movements

By comparing the movements of the countries in the world, it can bring forward insights into which regions currently lead the IoT and CPS markets, and which regions will lead in the future. Figure 5 is a graph of the number of published papers found on SCOPUS sorted into the top 15 countries. The searching term used was: "(TITLE-ABS-KEY(((("Internet of Things") OR ("Cyber Physical Systems"))) AND ("Manufacturing")))". This specifically searches all papers title, abstract, and keywords for the terms "manufacturing" and either "internet of things" or "cyber physical systems" or both.

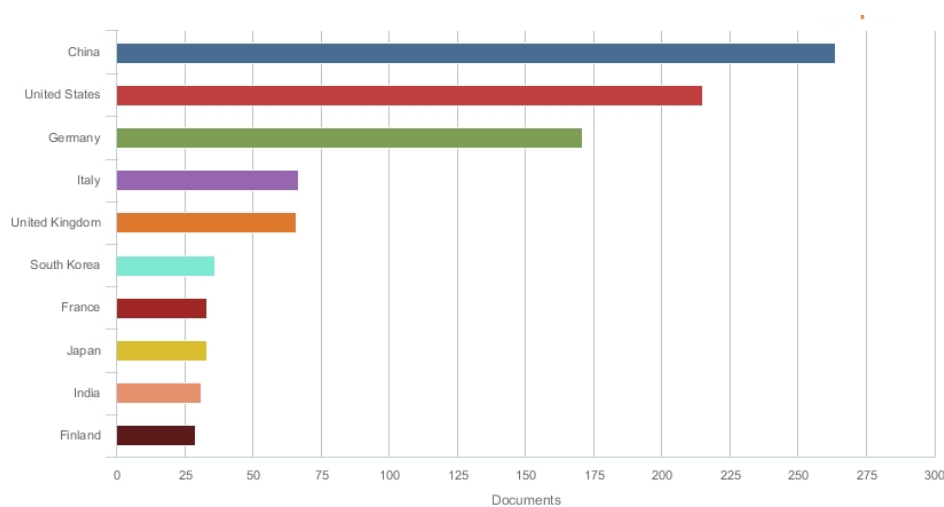


Figure 5. Publications from SCOPUS

It can be seen that the Asia Pacific region clearly leads in the number of publications, with the European Union behind, and North America in last. This is not too surprising, considering the Asia Pacific region has the largest manufacturing market (\$4.9 trillion USD as of 2013), with Europe also coming in second (\$2.6 trillion USD as of 2015), leaving North America last (\$2.4 trillion USD as of 2015). This means the Asia Pacific region has the most to gain from developments in IoT.

Many sources have attempted to estimate the future of IoT. Gartner predicts that in 2020 there will be 26 billion units, compared to the 0.9 billion units recorded in 2009, due to the low cost of adding IoT capabilities to consumer devices (Rivera, van der Meulen 2013). Cisco has predicted that by 2020 there will be 50 billion connected devices on the internet (Evans 2011). Statista also predicts 50 billion connected devices by 2020, with an observed 14.4 billion devices in 2014 (statista 2016a). The 50 billion estimate however has been retracted by the original author, and placed around 30 billion, which is more in line with the current estimates (Nordrum 2016). Therefore it is commonly agreed that there will be approximately 20 to 30 billion connected devices by 2020, a massive number of connected devices when compared to the human population.

Another way to gain insight into the future of IoT markets is to look at the sensor market (Perera, Liu et al. 2014). According to BCC Research's 2014 Market report, the estimated compounded annual growth rate between 2015 to 2020 for the sensor market is 10.1% per year, growing from a \$95.3 billion market to an estimated \$154.5 billion. Additionally, the RFID market is expected to grow from \$12.6 billion in 2016 to \$24.5 billion in 2020 (Statista 2016b). The growth in both these markets can be indicative the coming growth in IoT and CPS applications, as they require sensors as a perception layer.

We can also compare the expected benefits and adoption rates of IoT. A 2015 report by Tata Consultancy Services suggests that adoption of IoT is biggest in North America and Europe.

Of the surveyed companies, North American companies spend an average of 0.45% of revenue on IoT initiatives, whilst European companies spend 0.40% of revenue. Asia-Pacific companies spend 0.34%. Manufacturing companies also reported the highest revenue increase of 27% when compared to other global industry sectors in the year of 2014. In 2014, it was observed that manufacturing companies spend an average of 0.57% of revenue on IoT initiatives, an average of \$121 million US (Tata Consultancy Services Limited 2015).

In a separate survey of 465 business professionals in late 2015, it was estimated that 29% were using IoT at the time, with an additional 14% planning for implementation within 12 months, and another 21% planning implementation after that (Gartner Inc. 2016). This means 64% currently use or eventually plan to implement IoT strategies. It should also be noted that 28% do not plan to implement IoT and 9% see no relevance in it whatsoever. However there are two major hurdles identified, the first being business related and the second being organization related. Businesses do not yet know the full benefits IoT can yield and have not yet invested the time to determine what IoT can bring to their business. The organizational problem is lack of IoT expertise within the staff. Since it is a reasonably new concept, it is not surprising that many companies do not have people with expertise in that area.

3.5. Discussion

It should be clear that IoT and CPS strategies are widely expected to grow, in terms of the number of connected devices and market size. It is also reasonable to extend this to IoT and CPS strategies within a manufacturing context, in fact it may even be led by manufacturing, as hinted in (Tata Consultancy Services Limited 2015), with the industrial manufacturing sector as the second highest spending per revenue, and with the highest revenue impact. The natural extension of this growth is the widespread adoption within industry. Companies that fail to adopt this paradigm will most likely fail in the future, as they will slowly be outperformed due

to the relatively large marginal increases in efficiency IoT and CPS can bring. This is similar to what happened to Motorola.

This growth can also induce a positive feedback loop. As more companies incorporate IoT technologies as part of operations, more data is generated and shared. Algorithms may extract and confirm more hidden information from the larger data set, yielding more benefits, thus looking more attractive and causing more people to want to adopt IoT strategies.

From the review of technology and world-wide movements, several insights and lessons are obtained so that industrial practitioners and academia could be guided when they are contemplating IoT-enabled manufacturing application and research. Several lessons could be obtained from the review investigation. Firstly, IoT key technologies like RFID, Bar-code, and wireless communication standards are quite mature in industry applications. However, their integrations such as technical and data integration are scarcely reported. That may result in isolated technology implementation in entire manufacturing sites. For example, parts being produced communicate with machines by means of a product code, which tells the machines their production requirements and which steps need to be taken next and all processes are optimized for IT control, resulting in a minimal failure rate.

Secondly, successful cases are seldom reported since most of the implementation of IoT-enabled manufacturing is still in the initiative stage. Best practices and case studies require more implementations of IoT technology in the industry so that manufacturing could be better transformed and upgraded.

Thirdly, the IoT-enabled manufacturing is still led by developed countries like US and Germany. For example, most of the top IoT technology providers are from these countries. Few of them are from developing countries like China and India. Developing countries like China are chasing rapidly due to the government plans or programs. In the near future, these countries may be the biggest market for IoT technology and their applications.

Manufacturing worldwide is on the cusp of a revolution where new information technologies are suddenly offering not only to make the management of manufacturing more effective from early versions of plant and enterprise software, but the work itself smarter. Technologies based on the Internet of Things have the potential to radically improve visibility in manufacturing to the point where each unit of production can be “seen” at each step in the production process. Batch-level visibility is being replaced by unit-level visibility. This is the dawn of IoT-enabled manufacturing. IoT-enabled manufacturing requires a healthy dose of technology to ensure machines work together, material flows visibly in real time, and teams of knowledge workers orchestrate the entire manufacturing process. The IoT-based environment enables this possibility, for example in plant floor applications, it can create a network linking a range of manufacturing assets from production equipment to parts being produced, from sensor-embedded automation controls to energy meters, from trucks to a warehouse’s smart shelves (Zhong, Peng et al. 2017).

With the IoT, manufacturers can give each of their physical assets a digital identity that enables them to know the exact location and condition of those assets in real time ubiquitously throughout the manufacturing sites or even the whole supply chain. Very importantly, IoT-enabled manufacturing also requires proactive and autonomic analytics capabilities, making manufacturing an intelligent and self-healing environment. With IoT-enabled manufacturing, companies can predictively meet business needs through intelligent and automated actions driven by previously inaccessible insights from the real world. It transforms manufacturing businesses into proactive, autonomic organizations that predict and fix potentially disruptive issues, evolve operations and delight customers, all while increasing the bottom line.

4. APPLICATIONS

Despite what seems to be a lack of adoption of intelligent strategies for manufacturing, there are still many large companies that have successfully utilized them to enhance efficiency. In terms of new technological adoption, it is generally the larger or newer companies that adopt first, because they either have the money to spare, or they can implement without retrofitting. Small and medium sized companies that are already established would have to either retrofit existing infrastructure, or replace them, maybe even both. This can be implied from (Tata Consultancy Services Limited 2015), indicated by the difference between median and mean amounts companies spend on IoT initiatives in 2015. The mean is \$86 million USD, whilst median is \$4.2 million USD. This big difference is due to outlier companies spending extremely large amounts on IoT initiatives, drastically changing the mean but not the median.

One such company is Siemen's Electronics Manufacturing Plant, located in Amberg (Kreutzer 2014), (Hessman 2013). This factory produces PLCs, achieving a 99.9985% quality of production through the use of intelligent manufacturing strategies. To put this into perspective, the factory produces approximately 12 million units per year, of this only 180 of them will be defective. Machines and computers handle 75% of the value chain via automation, each product dictating their own production process. As a product approaches a machine, its product code is communicated to the machine informing it of what requirements the product has or needs, and what needs to be done. This demonstrates the automation power intelligent strategies can bring to the shop floor. The extension of this would be automatic process optimization, such as a generating a priority order of products based on upcoming deadlines. In addition to this, the factory can achieve 100% traceability as it generates around 50 million pieces of process information every day.

Siemen's also has an Electronics Work plant in Chengdu, China. Although the intelligent strategies are not as deeply integrated as the Amberg plant, it still manages to save approximately \$116,000 Euros through energy efficiency savings. Another company that has derived benefits from IoT is Rolls-Royce. They have over 13,000 commercial aircraft engines which they produce and maintain. IoT allows them to utilize predictive maintenance on these engines, which is aptly named their Engine Health Management (EHM) program (Rolls-Royce 2016), (Microsoft 2016).

Each engine is fitted with about 25 sensors, providing information about its state and environment, with many for pressure and temperature, vibration, etc. This aggregated over every engine results in "terabytes of data coming from large aircraft fleets, with gigabytes per hour – rather than kilobytes – to process and analyze", quoted by the Senior Vice President of Rolls-Royce, Nick Farrant.

Once the data is acquired, it is transferred and analyzed. These analysis algorithms use big data and artificial intelligence applications, utilizing techniques such as neural networks. If abnormal behavior is detected, engineers and analysts will confirm the behavior, and produce a diagnosis and prognosis. From this point, maintenance is planned, usually within a few flights. This type of maintenance removes the need for constant maintenance which the engine may not need, and improves safety if the quality of the engine declines faster than normal. Thus it increases business efficiency and decreases costs for both the airline and Rolls-Royce, translating to decreased operation cost, lower prices for consumers, resulting in a more attractive business.

General Electric's Durathon battery factory is another such company that has achieved success by adopting IoT and CPS within their manufacturing process (Stephenson 2014). The factory incorporates over 10,000 sensors on the assembly line, with additional sensors within the batteries themselves. This allows managers to know the entire state of the assembly line,

products, and machinery in real time, as opposed to aggregating manually entered data at the end of the day or cycle. This can cut operating costs and resource use. All information generated can also be shared, and expert analysis and maintenance can even be done offsite by looking at the data and having a local engineer execute the actions. It should be noted that the plant has since closed down, not due to the intelligent strategies it employed, but rather due to the early developmental phases of sodium ion batteries it was producing and its low demand (St. John 2015).

5. CONCLUSIONS

Industry 4.0, well-known as ‘smart factory’, was proposed in Germany with the modular structured smart factories, Internet of Things (IoT), and other technologies for creating a virtual version of the physical world so as to make decentralized decisions (Lee, Bagheri et al. 2015). Modern manufacturing sites such as factories, assembly lines/stations, shop floors are suffering from lack of data collection since paper and manual based systems are widely used. This paper reviews the current Internet of Things for manufacturing in terms of key technologies and world-wide movements. IoT-enabled manufacturing is about creating an environment where all available information from within the plant floor is captured in real-time, made visible and turned into actionable insights. It involves all aspects of business, blurring the boundaries among plant operations, supply chain, product design and demand management. Enabling virtual tracking of capital assets, processes, resources and products, IoT-enabled manufacturing gives enterprises full visibility which in turn supports streamlining business processes and optimizing supply and demand.

Some key technologies and world-wide applications are reviewed so that some critical insights and lessons could be obtained. Such important insights could be used for guiding

practitioners and academia in their applications and research in the near future due to the development of Industry 4.0.

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REFERENCES

- Abdullah, S., W. Ismail and Z. A. Halim (2015). "Implementation of Wireless RFID for Production Line Management System in a Real Environment." *Wireless personal communications* 83(4): 3119-3132.
- Ahmad, M. Y. and A. S. Mohan (2014). "Novel bridge-loop reader for positioning with HF RFID under sparse tag grid." *IEEE Transactions on Industrial Electronics* 61(1): 555-566.
- Almada-Lobo, F. (2016). "The Industry 4.0 revolution and the future of manufacturing execution systems (MES)." *Journal of Innovation Management* 3(4): 16-21.
- Al-fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M. and Ayyash, M., 2015. Internet of things: A survey on enabling technologies, protocols, and applications. *IEEE Communications Surveys & Tutorials*, 17(4), pp. 2347-2376.
- Atzori, L., Iera, A. and Morabito, G., 2010. The internet of things: A survey. *Computer networks*, 54(15), pp. 2787-2805.
- Baheti, R. and Gill, H., 2011. Cyber-physical systems. *The impact of control technology*, 12, pp. 161-166.

- Bandyopadhyay, D. and Sen, J., 2011. Internet of things: Applications and challenges in technology and standardization. *Wireless Personal Communications*, 58(1), pp. 49-69.
- Barenji, R. V., A. V. Barenji and M. Hashemipour (2014). "A multi-agent RFID-enabled distributed control system for a flexible manufacturing shop." *The International Journal of Advanced Manufacturing Technology* 71(9-12): 1773-1791.
- Bi, Z. M., L. D. Xu and C. G. Wang (2014). "Internet of things for enterprise systems of modern manufacturing." *IEEE Transactions on industrial informatics* 10(2): 1537-1546.
- Bin, S., Yuan, L. and Xiaoyi, W., 2010. Research on data mining models for the internet of things, 2010 International Conference on Image Analysis and Signal Processing 2010, IEEE, pp. 127-132.
- Cannata, A., Gerosa, M. and Taisch, M., 2008. SOCRADES: A framework for developing intelligent systems in manufacturing, 2008 IEEE International Conference on Industrial Engineering and Engineering Management 2008, IEEE, pp. 1904-1908.
- Chen, C., S. L. Pan, Z. G. Wang and R. Y. Zhong (2017). "Using taxis to collect citywide E-commerce reverse flows: a crowdsourcing solution." *International Journal of Production Research* 55(7): 1833-1844.
- Chen, F., Deng, P., Wan, J., Zhang, D., Vasilakos, A.V. and Rong, X., 2015. Data mining for the internet of things: literature review and challenges. *International Journal of Distributed Sensor Networks*, 2015, pp. 12.
- Collignon, H., Vincent, J., Broquist, M. and Kratzert, T., 2016. *The Internet of Things: A New Path to European Prosperity*. A.T. Kearney.
- Cordis, 2016-last update, CORDIS is the Community Research and Development Information Service. Available: http://cordis.europa.eu/guidance/home_en.html [December/21, 2016].

- Dai, Q. Y., R. Y. Zhong, G. Q. Huang, T. Qu, T. Zhang and T. Y. Luo (2012). "Radio frequency identification-enabled real-time manufacturing execution system: a case study in an automotive part manufacturer." *International Journal of Computer Integrated Manufacturing* 25(1): 51-65.
- Dai, Q. Y., R. Y. Zhong, K. Zhou and Z. Y. Jiang (2010). A RFID-enabled real-time manufacturing hardware platform for discrete industry. *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology*, 1743-1750, Springer.
- DIGITAL SINGLE MARKET, Why we need a Digital Single Market.
- Dillon, T.S., Zhuge, H., Wu, C., Singh, J. and Chang, E., 2011. Web - of - things framework for cyber - physical systems. *Concurrency and Computation: Practice and Experience*, 23(9), pp. 905-923.
- Dimakopoulou, A. G., K. C. Pramatari and A. E. Tsekrekos (2014). "Applying real Options to IT investment evaluation: The case of radio frequency identification (RFID) technology in the supply chain." *International Journal of Production Economics* 156: 191-207.
- Dobkin, D.M. and Wandinger, T., 2005. A Radio Oriented Introduction to Radio Frequency Identification. *RFID Tutorial, High Frequency Electronics*, , pp. 46-54.
- Domingo, M.C., 2012. An overview of the Internet of Things for people with disabilities. *Journal of Network and Computer Applications*, 35(2), pp. 584-596.
- Drath, R. and Horch, A., 2014. Industrie 4.0: Hit or hype?[industry forum]. *IEEE industrial electronics magazine*, 8(2), pp. 56-58.
- Dubey, R., A. Gunasekaran and A. Chakrabarty (2017). "Ubiquitous manufacturing: overview, framework and further research directions." *International Journal of Computer Integrated Manufacturing* 30(4-5): 381-394.

EUROPEAN COMMISSION, 2015-last update, What is Horizon 2020?. Available: <https://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020> [December/24, 2016].

Evans, D., 2011. *The Internet of Things: How the Next Evolution of the Internet Is Changing Everything*. Cisco.

Gao, R., Wang, L. H, Teti, R., Dornfeld, D., Kumara, S., Mori, M. and Helu, M., 2015. Cloud-enabled prognosis for manufacturing. *CIRP Annals-Manufacturing Technology*, 64(2), pp. 749-772.

Fantoni, G., M. Santochi, G. Dini, K. Tracht, B. Scholz-Reiter, J. Fleischer, T. K. Lien, G. Seliger, G. Reinhart and J. Franke (2014). "Grasping devices and methods in automated production processes." *CIRP Annals-Manufacturing Technology* 63(2): 679-701.

GARTNER INC., 2016-last update, Gartner Survey Shows that 43 Percent of Organizations Are Using or Plan to Implement the Internet of Things in 2016. Available: <http://www.gartner.com/newsroom/id/3236718> [December/21, 2016].

GRAND VIEW RESEARCH, 2016-last update, IoT Market Analysis By Component (Devices, Connectivity, IT Services, Platforms), By Application (Consumer Electronics, Retail, Manufacturing, Transportation, Healthcare) And Segment Forecasts To 2022. Available: <http://www.grandviewresearch.com/industry-analysis/iot-market> [December/21, 2016].

Guinard, D., Trifa, V., Karnouskos, S., Spiess, P. and Savio, D., 2010. Interacting with the soa-based internet of things: Discovery, query, selection, and on-demand provisioning of web services. *IEEE transactions on Services Computing*, 3(3), pp. 223-235.

Haller, S., Karnouskos, S. and Schroth, C., 2008. *The internet of things in an enterprise context*, Future Internet Symposium 2008, Springer, pp. 14-28.

Heng, S., 2014-last update, Industry 4.0: Huge potential for value creation waiting to be tapped.

Available:

https://www.dbresearch.com/servlet/reweb2.ReWEB?rwsite=DBR_INTERNET_EN-PROD&rwobj=ReDisplay.Start.class&document=PROD0000000000335628

[December/21, 2016].

Hessman, T., 2013-last update, The Dawn of the Smart Factory. Available:

<http://www.industryweek.com/technology/dawn-smart-factory> [December/21, 2016].

Holfeld, B., D. Wieruch, T. Wirth, L. Thiele, S. A. Ashraf, J. Huschke, I. Aktas and J. Ansari

(2016). "Wireless Communication for Factory Automation: an opportunity for LTE and 5G systems." *IEEE Communications Magazine* 54(6): 36-43.

Huang, G. Q., Y. Zhang, X. Chen and S. T. Newman (2008). "RFID-enabled real-time wireless

manufacturing for adaptive assembly planning and control." *Journal of Intelligent Manufacturing* 19(6): 701-713.

Huang, G. Q, Wright, P. and Newman, S.T., 2009. Wireless manufacturing: a literature review,

recent developments, and case studies. *International Journal of Computer Integrated Manufacturing*, 22(7), pp. 579-594.

I4Ms - Enhancing the digital transformation of the European manufacturing sector. 2016.

innovalia Association., World Bank Open Data 2016-last update. Available: <http://data.worldbank.org/> [12/29, 2016].

Jazdi, N., 2014. Cyber physical systems in the context of Industry 4.0, Automation, Quality

and Testing, Robotics, 2014 IEEE International Conference on 2014, IEEE, pp. 1-4.

Jia, X., Feng, Q., Fan, T. and Lei, Q., 2012. RFID technology and its applications in Internet

of Things (IoT), Consumer Electronics, Communications and Networks (CECNet), 2012 2nd International Conference on 2012, IEEE, pp. 1282-1285.

- Karnouskos, S., Guinard, D., Savio, D., Spiess, P., Baecker, O., Trifa, V. and De souza, LUCIANA MOREIRA SÁ, 2009. Towards the real-time enterprise: service-based integration of heterogeneous SOA-ready industrial devices with enterprise applications. *IFAC Proceedings Volumes*, 42(4), pp. 2131-2136.
- Kopetz, H., 2011. Internet of things. Real-time systems. Springer, pp. 307-323.
- Kreutzer, U., 2014-last update, Defects: A Vanishing Species?. Available: <http://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/digital-factories-defects-a-vanishing-species.html> [December/21, 2016].
- Kretschmer, R., A. Pfouga, S. Rulhoff and J. Stjepandić (2017). "Knowledge-based design for assembly in agile manufacturing by using Data Mining methods." *Advanced Engineering Informatics*.
- Lai, C., Ma, Y., Chang, S., Chao, H. and Huang, Y., 2011. OSGi-based services architecture for cyber-physical home control systems. *Computer Communications*, 34(2), pp. 184-191.
- Lee, E.A., 2008. Cyber physical systems: Design challenges, 2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC) 2008, IEEE, pp. 363-369.
- Lee, J. and Lapira, E., 2013. Predictive factories: the next transformation. *Manufacturing Leadership Journal*, 20(1), pp. 13-24.
- Lee, J., Bagheri, B. and Kao, H., 2015. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, pp. 18-23.
- Lee, J., Lapira, E., Bagheri, B. and KAO, H., 2013. Recent advances and trends in predictive manufacturing systems in big data environment. *Manufacturing Letters*, 1(1), pp. 38-41.

- Lee, J., H.-A. Kao and S. Yang (2014). "Service innovation and smart analytics for industry 4.0 and big data environment." *Procedia Cirp* 16: 3-8.
- Lee, J., F. Wu, W. Zhao, M. Ghaffari, L. Liao and D. Siegel (2014). "Prognostics and health management design for rotary machinery systems—Reviews, methodology and applications." *Mechanical systems and signal processing* 42(1): 314-334.
- Leung, J., W. Cheung and S.-C. Chu (2014). "Aligning RFID applications with supply chain strategies." *Information & Management* 51(2): 260-269.
- Li, B., B. Hou, W. Yu, X.-b. Lu and C.-w. Yang (2017). "Applications of artificial intelligence in intelligent manufacturing: a review." *Front. Inform. Technol. Electron. Eng* 18(1): 86-96.
- Li, S., Xu, L.D. and Zhao, S., 2015. The internet of things: a survey. *Information Systems Frontiers*, 17(2), pp. 243-259.
- Liu, C.H., Yang, B. and Liu, T., 2014. Efficient naming, addressing and profile services in Internet-of-Things sensory environments. *Ad Hoc Networks*, 18, pp. 85-101.
- Liu, Q., Gao, L. and Lou, P., 2011. Resource management based on multi-agent technology for cloud manufacturing, *Electronics, Communications and Control (ICECC)*, 2011 International Conference on 2011, IEEE, pp. 2821-2824.
- Liu, Y. and X. Xu (2017). "Industry 4.0 and Cloud Manufacturing: A Comparative Analysis." *Journal of Manufacturing Science and Engineering* 139(3): 034701.
- Lu, S., C. Xu and R. Y. Zhong (2016). "An Active RFID Tag-Enabled Locating Approach With Multipath Effect Elimination in AGV." *IEEE Transactions on Automation Science and Engineering* 13(3): 1333-1342.
- Lund, D., Turner, V., Macgillivray, C. and Morales, M., 2014. Worldwide and Regional Internet of Things (IoT) 2014–2020 Forecast: A Virtuous Circle of Proven Value and Demand. International Data Corporation (IDC).

Makris, S., G. Michalos and G. Chryssolouris (2012). "RFID driven robotic assembly for random mix manufacturing." *Robotics and Computer-Integrated Manufacturing* 28(3): 359-365.

Mejjaoui, S. and R. F. Babiceanu (2015). "RFID-wireless sensor networks integration: Decision models and optimization of logistics systems operations." *Journal of Manufacturing Systems* 35: 234-245.

MICROMARKETMONITOR, 2016-last update, North America Internet-of-Things (IoT) and Machine-to-Machine (M2M) Communication Market. Available: <http://www.micromarketmonitor.com/market/north-america-internet-of-things-iot-and-machine-to-machine-m2m-communication-5465720547.html> [December/21, 2016].

MICROSOFT, 2016-last update, Rolls-Royce and Microsoft collaborate to create new digital capabilities. Available: <https://customers.microsoft.com/en-US/story/rollsroycestory> [December/21, 2016].

Mo, Y. and Sinopoli, B., 2009. Secure control against replay attacks, *Communication, Control, and Computing*, 2009. Allerton 2009. 47th Annual Allerton Conference on 2009, IEEE, pp. 911-918.

Nordrum, A., 2016-last update, Popular Internet of Things Forecast of 50 Billion Devices by 2020 Is Outdated. Available: <http://spectrum.ieee.org/tech-talk/telecom/internet/popular-internet-of-things-forecast-of-50-billion-devices-by-2020-is-outdated> [December/21, 2016].

Peng, Y. H. (2008). The research of wireless manufacturing network based on Bluetooth technology. *International Symposium on Information Science and Engineering*, 457-460, IEEE.

- Perera, C., Liu, C.H., Jayawardena, S. and Chen, M., 2014. A survey on internet of things from industrial market perspective. *IEEE Access*, 2, pp. 1660-1679.
- Petnga, L. and M. Austin (2016). "An ontological framework for knowledge modeling and decision support in cyber-physical systems." *Advanced Engineering Informatics* 30(1): 77-94.
- PWC, 2015. *The Internet of Things: What it means for US manufacturing*. PwC.
- Rajesh, V., J. Gnanasekar, R. Ponmagal and P. Anbalagan (2010). Integration of wireless sensor network with cloud. 2010 International Conference on Recent Trends in Information, Telecommunication and Computing (ITC), 321-323, IEEE.
- Rivera, J. and Van der meulen, R., 2013. Gartner says the internet of things installed base will grow to 26 billion units by 2020. Stamford, conn., December, 12.
- ROLLS-ROYCE, 2016-last update, Engine Health Management. Available: <http://www.rolls-royce.com/about/our-technology/enabling-technologies/engine-health-management.aspx#sense> [December/21, 2016].
- Saab, S. S. and H. Msheik (2016). "Novel RFID-Based Pose Estimation Using Single Stationary Antenna." *IEEE Transactions on Industrial Electronics* 63(3): 1842-1852.
- Sadeghi, A., Wachsmann, C. and Waidner, M., 2015. Security and privacy challenges in industrial internet of things, *Proceedings of the 52nd Annual Design Automation Conference 2015*, ACM, pp. 54.
- Sanislav, T. and Miclea, L., 2012. Cyber-physical systems-concept, challenges and research areas. *Journal of Control Engineering and Applied Informatics*, 14(2), pp. 28-33.
- Schweer, D. and J. C. Sahl (2017). *The Digital Transformation of Industry—The Benefit for Germany. The Drivers of Digital Transformation*, Springer: 23-31.

Shi, J., Wan, J., Yan, H. and Suo, H., 2011. A survey of cyber-physical systems, *Wireless Communications and Signal Processing (WCSP), 2011 International Conference on 2011, IEEE*, pp. 1-6.

Smartanythingeverywhere, 2015-last update, Digital Innovation Initiatives based on European Networks of Competence Centres in H2020. Available: <https://smartanythingeverywhere.eu/smart-anything-everywhere/> [December/21, 2016].

Spiess, P., Karnouskos, S., Guinard, D., Savio, D., Baecker, O., DE SOUZA, Luciana Moreira SÁ and Trifa, V., 2009. SOA-based integration of the internet of things in enterprise services, *Web Services, 2009. ICWS 2009. IEEE International Conference on 2009, IEEE*, pp. 968-975.

St. John, J., 2015-last update, GE scales back production of grid-scale durathon batteries. available: <https://www.greentechmedia.com/articles/read/ge-scales-back-production-of-grid-scale-durathon-batteries> [december/21, 2016].

Statista, 2016a-last update, Internet of Things (IoT): number of connected devices worldwide from 2012 to 2020 (in billions). available: <https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/> [december/21, 2016].

Statista, 2016b-last update, projected size of the global market for RFID tags from 2016 to 2020 (in billion u.s. dollars). available: <https://www.statista.com/statistics/299966/size-of-the-global-rfid-market/> [december/21, 2016].

Statista, 2016c-last update, revenue of the Internet of Things in asia/pacific from 2013 to 2020 (in billion u.s. dollars). available: <https://www.statista.com/statistics/512238/iot-revenue-asia-pacific/> [december/21, 2016].

- Stephenson, D., 2014-last update, the Internet of Things: enabling the era of precision manufacturing. available: <http://radar.oreilly.com/2014/04/the-internet-of-things-enabling-the-era-of-precision-manufacturing.html> [december/21, 2016].
- Sztipanovits, J., Koutsoukos, X., Karsai, G., Kottenstette, N., Antsaklis, P., Gupta, V., Goodwine, B., Baras, J. and Wang, S., 2012. toward a science of cyber–physical system integration. *proceedings of the IEEE*, 100(1), pp. 29-44.
- Tan, Y., Goddard, S. and Perez, L.C., 2008. A prototype architecture for cyber-physical systems. *ACM Sigbed Review*, 5(1), pp. 26.
- Tao, F., Zhang, L., Venkatesh, V., Luo, Y. and Cheng, Y., 2011. Cloud manufacturing: a computing and service-oriented manufacturing model. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, , pp. 0954405411405575.
- Tao, F., Cheng, Y., Xu, L. D., Zhang, L. and Li, B.H., 2014. CCIoT-CMfg: cloud computing and internet of things-based cloud manufacturing service system. *IEEE Transactions on Industrial Informatics*, 10(2), pp. 1435-1442.
- Tao, F., Zuo, Y., Xu, L. D. and Zhang, L., 2014. IoT-based intelligent perception and access of manufacturing resource toward cloud manufacturing. *IEEE Transactions on Industrial Informatics*, 10(2), pp. 1547-1557.
- Tao, F., Y. Cheng, L. Da Xu, L. Zhang and B. H. Li (2014). "CCIoT-CMfg: cloud computing and internet of things-based cloud manufacturing service system." *IEEE Transactions on Industrial Informatics* 10(2): 1435-1442.
- Tata consultancy services limited, 2015. *Internet of Things: The Complete Reimaginative Force*. Tata Consultancy Services Limited.

- Tesch, D. A., E. L. Berz and F. P. Hessel (2015). RFID indoor localization based on Doppler effect. *Quality Electronic Design (ISQED)*, 2015 16th International Symposium on, IEEE.
- Trappey, A. J., Trappey, C. V., Govindarajan, U. H., Chuang, A. C., and Sun, J. J. (2016). A review of essential standards and patent landscapes for the Internet of Things: A key enabler for Industry 4.0. *Advanced Engineering Informatics* 10.1016/j.aei.2016.11.007
- Uckelmann, D., Harrison, M. and Michahelles, F., 2011. An architectural approach towards the future internet of things. *Architecting the internet of things*. Springer, pp. 1-24.
- Van kranenburg, R., Anzelmo, E., Bassi, A., Caprio, D., Dodson, S. and Ratto, M., 2011. The internet of things. A critique of ambient technology and the all-seeing network of RFID, *Network Notebooks*, 2.
- Virkkala, S. (2007). "Innovation and networking in peripheral areas—a case study of emergence and change in rural manufacturing." *European Planning Studies* 15(4): 511-529.
- Wan, J., Chen, M., Xia, F., Li, D. and Zhou, K., 2013. From machine-to-machine communications towards cyber-physical systems. *Comput.Sci.Inf.Syst.*, 10(3), pp. 1105-1128.
- Wang, F., 2010. The emergence of intelligent enterprises: From CPS to CPSS. *IEEE Intelligent Systems*, 25(4), pp. 85-88.
- Wang, L., Xu, L.D., Bi, Z. and Xu, Y., 2014. Data cleaning for RFID and WSN integration. *IEEE Transactions on Industrial Informatics*, 10(1), pp. 408-418.
- Wang, L. H., M. Törngren and M. Onori (2015). "Current status and advancement of cyber-physical systems in manufacturing." *Journal of Manufacturing Systems* 37(Part 2): 517-527.

- Wang, M. L., T. Qu, R. Y. Zhong, Q. Y. Dai, X. W. Zhang and J. B. He (2012). "A radio frequency identification-enabled real-time manufacturing execution system for one-of-a-kind production manufacturing: a case study in mould industry." *International Journal of Computer Integrated Manufacturing* 25(1): 20-34.
- Wang, M. L., R. Y. Zhong, Q. Y. Dai and G. Q. Huang (2016). "A MPN-based scheduling model for IoT-enabled hybrid flow shop manufacturing." *Advanced Engineering Informatics* 30(4): 728-736.
- Wu, N. and M. Zhou (2007). "Deadlock resolution in automated manufacturing systems with robots." *IEEE Transactions on Automation Science and Engineering* 4(3): 474-480.
- Xu, L.D, He, W. and Li, S., 2014. Internet of things in industries: A survey. *IEEE Transactions on Industrial Informatics*, 10(4), pp. 2233-2243.
- Xu, X. (2012). "From cloud computing to cloud manufacturing." *Robotics and computer-integrated manufacturing* 28(1): 75-86.
- Xu, X. (2017). "Machine Tool 4.0 for the new era of manufacturing." *The International Journal of Advanced Manufacturing Technology*: 1-8.
- Yick, J., Mukherjee, B. and Ghosal, D., 2008. Wireless sensor network survey. *Computer networks*, 52(12), pp. 2292-2330.
- Yun, M. and Yuxin, B., 2010. Research on the architecture and key technology of Internet of Things (IoT) applied on smart grid, *Advances in Energy Engineering (ICAEE)*, 2010 International Conference on 2010, IEEE, pp. 69-72.
- Zhang, H. and Zhu, L., 2011. Internet of Things: Key technology, architecture and challenging problems, *Computer Science and Automation Engineering (CSAE)*, 2011 IEEE International Conference on 2011, IEEE, pp. 507-512.

- Zhang, Y., T. Qu, O. K. Ho and G. Q. Huang (2011). "Agent-based smart gateway for RFID-enabled real-time wireless manufacturing." *International Journal of Production Research* 49(5): 1337-1352.
- Zhong, R. Y., Q. Dai, T. Qu, G. Hu and G. Q. Huang (2013). "RFID-enabled real-time manufacturing execution system for mass-customization production." *Robotics and Computer-Integrated Manufacturing* 29(2): 283-292.
- Zhong, R. Y., H. Gong, C. Xu and S. Lu (2016). "Physical Internet-Enabled Manufacturing Execution System for Intelligent Workshop Production." *International Journal of Signal Processing, Image Processing and Pattern Recognition* 9(6): 121-132.
- Zhong, R. Y., and Huang, G. Q. (2014a). RFID-enabled Learning Supply Chain: A Smart Pedagogical Environment for TELD. *International Journal of Engineering Education*, 30(2), 471-482.
- Zhong, R. Y., G. Q. Huang and Q. Y. Dai (2014b). "A Big Data Cleansing Approach for n-dimensional RFID-Cuboids." *Proceeding of the 2014 IEEE 18th International Conference on Computer Supported Cooperative Work in Design (CSCWD 2014)*, 21-23 May, Taiwan: 289-294.
- Zhong, R. Y., G. Q. Huang, Q. Y. Dai and T. Zhang (2014c). "Mining SOTs and Dispatching Rules from RFID-enabled Real-time Shopfloor Production Data." *Journal of Intelligent Manufacturing*. 25(4): 825-843.
- Zhong, R. Y., G. Q. Huang, S. Lan, Q. Dai, T. Zhang and C. Xu (2015a). "A two-level advanced production planning and scheduling model for RFID-enabled ubiquitous manufacturing." *Advanced Engineering Informatics* 29(4): 799-812.
- Zhong, R. Y., G. Q. Huang, S. L. Lan, Q. Y. Dai, C. Xu and T. Zhang (2015b). "A Big Data Approach for Logistics Trajectory Discovery from RFID-enabled Production Data." *International Journal of Production Economics* 165: 260-272.

- Zhong, R. Y., S. Lan, C. Xu, Q. Dai and G. Q. Huang (2016). "Visualization of RFID-enabled shopfloor logistics Big Data in Cloud Manufacturing." *The International Journal of Advanced Manufacturing Technology* 84(1): 5-16.
- Zhong, R. Y., Z. Li, A. L. Y. Pang, Y. Pan, T. Qu and G. Q. Huang (2013). "RFID-enabled Real-time Advanced Planning and Scheduling Shell for Production Decision-making." *International Journal of Computer Integrated Manufacturing*. 26(7): 649-662.
- Zhong, R. Y., S. T. Newman, G. Q. Huang and S. L. Lan (2016). "Big Data for supply chain management in the service and manufacturing sectors: Challenges, opportunities, and future perspectives." *Computers & Industrial Engineering* 101: 572-591.
- Zhong, R. Y., Y. Peng, F. Xue, J. Fang, W. Zou, H. Luo, S. T. Ng, W. Lu, G. Q. Shen and G. Q. Huang (2017). "Prefabricated construction enabled by the Internet-of-Things." *Automation in Construction* 76: 59-70.