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Cybersecurity for Industry 4.0

Analysis for Design and Manufacturing

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Preface

A transformative event known as Industry 4.0 is occurring where countless elements comprising industrial systems are being interfaced with internet communication technologies to form the smart factories and manufacturing organizations of the future. Industry 4.0 and its associated technologies, such as cloud-based design and manufacturing systems and the Industrial Internet of Things, are currently being driven by disruptive innovation that promises to bring countless new value creation opportunities across all major market sectors. However, existing internet technologies are plagued by cybersecurity and data privacy issues that will present major challenges and roadblocks for adopters of Industry 4.0 technologies. Industry 4.0 will face traditional cybersecurity issues along with its very own unique security and privacy challenges. If these challenges are not appropriately addressed, the true potential of Industry 4.0 may never be achieved.

The objective of this book is to provide an overview of cybersecurity for the Industry 4.0 landscape with an emphasis on Design and Manufacturing applications. It covers the technological foundations of cybersecurity within this domain and addresses existing threats faced by Industry 4.0 sectors along with existing state-of-the-art solutions. To provide a holistic perspective, the topic is discussed from the perspectives of both practical implementations in industry and cutting-edge academic research. This way, it benefits practicing engineers and decision makers in industry as well as researchers and educators in the design and manufacturing communities.

In Chapter "Industry 4.0: An Overview of Key Benefits, Technologies, and Challenges", Thames and Schaefer provide details of Industry 4.0 technologies and paradigms in order to provide the reader with a good background of Industry 4.0 basics. The purpose of this chapter is to give the reader a better understanding of the cybersecurity aspects of the remaining chapters in the book.

In Chapter "Customized Encryption of CAD Models for Cloud-Enabled Collaborative Product Development", Cai, Wang, Lu, and Li introduce an innovative and customized encryption approach to support secure product development collaboration. Their goal is to maintain the security of the sensitive information in

CAD models while sharing other information of the models in the cloud for effective collaboration.

Wegner, Graham, and Ribble introduce in Chapter “A New Approach To Cyberphysical Security in Industry 4.0”, titled a new paradigm using a direct-to-machine communication approach that limits and protects information flows to internal and subcontracted factory floor devices to complement perimeter security. The authors believe this to be an essential first step in creating secure manufacturing for Industry 4.0.

Chapter “SCADA System Forensic Analysis Within IIoT” introduces the reader to Forensic Analysis within the Industrial Internet of Things (IIoT). In this chapter titled “SCADA System Forensic Analysis within IIoT”, Eden et al. focus on the need for incident response when incidents occur within Industry 4.0 environments. The chapter focusses on the forensic challenges and analysis within an IIoT and its physical infrastructure.

In Chapter “Big Data Security Intelligence for Healthcare Industry 4.0”, Manogaran et al. provide an overview of how the healthcare industry can be viewed as an Industry 4.0 paradigm. The healthcare industry has started using many types of Internet of Things (IoT) and Industrial Internet of Things (IIoT) technologies. The data generated by healthcare ‘things’ should be managed with security and privacy in mind. The authors introduce their Meta Cloud-Redirection architecture and describe the security and privacy aspects of it.

In Chapter “Decentralized Cyber-Physical Systems: A Paradigm for Cloud-Based Smart Factory of Industry 4.0” Zhang et al. introduce the conceptual model and operation mechanism of decentralized cyber-physical systems (CPS), which enables manufacturers to utilize a cloud-based agent approach to create an intelligent collaborative environment for product creation. Similar to Chapter “Industry 4.0: An Overview of Key Benefits, Technologies, and Challenges”, Chapter “Decentralized Cyber-Physical Systems: A Paradigm for Cloud-Based Smart Factory of Industry 4.0” details many key underlying technologies of Industry 4.0.

Chapter “Applying and Assessing Cybersecurity Controls for Direct Digital Manufacturing (DDM) Systems” introduces the reader to direct digital manufacturing and its cybersecurity needs. In this chapter, Glavach, LaSalle-DeSantis, and Zimmerman address cybersecurity threats to the DDM community. They provide a case study detailing a security assessment performed on an additive manufacturing system and present protocols and recommendations for security best practices for DDM systems.

In Chapter “The Resource Usage Viewpoint of Industrial Control System Security: An Inference-Based Intrusion Detection System”, Nair et al. introduce cybersecurity mechanisms for Industrial Control Systems. Their premise is that one can infer CPU load by remotely profiling the network traffic emitted by an ICS device and use that inference to detect potentially malicious modifications to the behavior of the ICS device.

In Chapter “Practical Security Aspects of the Internet of Things”, Mehnen et al. introduce a set of key security issues related to the implementation of the Internet of

Things (IoT) in an industrial mechanical engineering context. The authors provide a real-world example concerning remote maintenance of CNC machine tools, which illustrates the different threat scenarios related to IoT in practice. The authors detail various aspects of Big Data and Cloud Manufacturing but focus on improving security at the Edge of IoT, which is where data is collected, transmitted and eventually transferred back to the physical actuators. The authors' aim is to introduce a generic overview of real-world IoT security issues as well as giving a deeper technical example-supported insight into practical considerations for designing IoT systems for practical use in business.

Finally, the book concludes with Chapter "Cybersecurity for Industry 4.0 and Advanced Manufacturing Environments with Ensemble Intelligence". In this final chapter, Thames and Schaefer discuss how machine learning approaches using ensemble intelligence can be achieved. Particularly, the authors describe how cyberattack detection and response mechanisms were integrated into a Software-Defined Cloud Manufacturing architecture. The cyberattack detection algorithm described in this chapter is based on ensemble intelligence with neural networks whose outputs are fed into a neuro-evolved neural network oracle. The oracle produces an optimized classification output that is used to provide feedback to active attack response mechanisms within the software-defined cloud manufacturing system. The underlying goal of this chapter is to show how computational intelligence approaches can be used to defend critical Industry 4.0 systems as well as other Internet-driven systems.

This book is one of the first collections of works related to various aspects of Industry 4.0 and its cybersecurity needs. We hope you find it to be informative and useful for your cybersecurity and Industry 4.0 research efforts.

Atlanta, USA
Bath, UK
Winter 2016/2017

Lane Thames, Ph.D.
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Industry 4.0: An Overview of Key Benefits, Technologies, and Challenges

Lane Thames and Dirk Schaefer

Abstract A new revolution known as Industry 4.0 is occurring where countless elements comprising industrial systems are being interfaced with internet communication technologies to form the smart factories and manufacturing organizations of the future. Industry 4.0 and its associated technologies are currently being driven by disruptive innovation that promises to bring countless new value creation opportunities across all major market sectors. However, existing Internet technologies are plagued by cybersecurity and data privacy issues that will present major challenges and roadblocks for adopters of Industry 4.0 technologies. Industry 4.0 will face traditional cybersecurity issues along with its very own unique security and privacy challenges. If these challenges are not appropriately addressed, the true potential of Industry 4.0 may never be achieved. This chapter provides a brief overview of several key Industry 4.0 technologies and paradigms in order to give the reader a better understanding of the cybersecurity aspects of the remaining chapters in the book.

1 Introduction: Background and Motivation

A transformative event known as Industry 4.0 is occurring where countless elements comprising industrial systems are being interfaced with internet communication technologies to form the smart factories and manufacturing organizations of the future. Industry 4.0 and its associated technologies such as cloud-based design and manufacturing systems, the Internet of Things, the Industrial Internet of Things, and Social-Product Development are currently being driven by disruptive innovation that promises to bring countless new value creation opportunities across all major market sectors. However, existing Internet technologies are plagued by cybersecurity and data privacy issues that will present major challenges and roadblocks for

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adopters of Industry 4.0 technologies. Industry 4.0 will face traditional cybersecurity issues along with its very own unique security and privacy challenges. If these challenges are not appropriately addressed, the true potential of Industry 4.0 may never be achieved.

A significant obstacle faced by those in Industry 4.0 related to cybersecurity is that of integration and cooperation amongst the stakeholders of any given Industry 4.0 organization. The core of this obstacle is that of language. Particularly, Industry 4.0 environments are made of diverse technologies spread across many disciplines with many different types of subject matter experts, but there are few standards and processes designed to assist each entity to speak a "common language" that appropriately aligns necessary objectives related to cybersecurity. For example, on the manufacturing side we have control engineers working with Operational Technology (OT). Similarly, on the Information Technology (IT) side we have system administrators working with traditional IT assets such as servers and software. On the one hand, a control engineer when dealing with securing OT assets is mostly concerned with 'mission assurance'. On the other hand, an IT system administrator is concerned with 'information assurance'. These objectives rarely align with one another. For example, a control engineer doesn't care about data loss over human life or machinery loss whereas a system administrator would never think about air gapping his battery backup units (UPS) for his servers. The drivers underlying these cybersecurity objects are vast and very different across domains. However, Industry 4.0 demands that these systems be integrated across all dimensions.

A primary goal of this book is to shed light on these aforementioned types of obstacles, needs, technologies and such as related to Industry 4.0 and cybersecurity. As alluded to in the previous paragraph, when approaching this subject, stakeholders need to understand the bigger picture. As such, the purpose of this chapter is to provide the reader with an overview of key technologies and paradigms related to Industry 4.0. The remainder of the book will emphasize cybersecurity aspects of Industry 4.0.

2 Industry 4.0 and Smart Manufacturing

Industry 4.0 is sometimes referred to as the 4th industrial revolution, and it is a vision of smart factories built with intelligent cyber-physical systems. It will enable manufacturing ecosystems driven by smart systems that have autonomic self-properties, for examples self-configuration, self-monitoring, and self-healing. Industry 4.0 will allow us to achieve unprecedented levels of operational efficiencies and accelerated growth in productivity. New types of advanced manufacturing and industrial processes revolving around machine-to-human collaboration and symbiotic product realization will emerge.

Industry 4.0 will encompass numerous technologies and associated paradigms. A few of these emerging paradigms include the Industrial Internet and the Industrial Internet of Things along with new 21st century product development paradigms such as cloud-based design, cloud-based manufacturing, crowd sourcing, and open innovation to name a few. A brief overview of these paradigms is provided in the following sections.

2.1 Industrial Internet and the Industrial Internet of Things

A new revolution is occurring within industry. It is a revolution resulting from the convergence of industrial systems with advanced computing, sensors and ubiquitous communication systems. It is a transformative event where countless industrial devices, both old and new, are beginning to use Internet Protocol (IP) communication technologies. We refer to this new revolution as the Industrial Internet of Things. The Industrial Internet of Things is a subset of what we have come to know as the Internet of Things (IoT). The IoT is an abstract idea that captures a movement that started when we began integrating computing and communication technology into many of the "things" that we use at home and work. It started with the idea of tagging and tracking "things" with low cost sensor technologies such as radio frequency identification (RFID) devices. However, the paradigm shifted as the market began delivering low-cost computing and Internet-based communication technologies, simultaneously with the rise of the ubiquitous smartphone.

This perfect storm of low cost computing and pervasive broadband networking has allowed the IoT to evolve. Now, the IoT includes all types of devices ranging from home appliances, light bulbs, automation systems, watches, to even our cars and trucks. Technically speaking, the IoT is a collection of physical artifacts that contain embedded systems of electrical, mechanical, computing and communication mechanisms that enable Internet-based communication and data exchange.

The Industrial IoT follows the same core definition of the IoT, but the things and goals of the Industrial IoT are usually different (see Fig. 1). Some examples of the things of the Industrial IoT include devices such as sensors, actuators, robots, manufacturing devices such as milling machines, 3D-printers, and assembly line components, chemical mixing tanks, engines, healthcare devices such as insulin and infusion pumps, and even planes, trains, and automobiles. Indeed, it is a vast spectrum of devices.

One interesting aspect of Industrial IoT devices is system complexity. In particular, Industrial IoT devices can contain systems of IoT systems. For example, an industrial robot as a whole might contain multiple sensors working both independently and as a group, and one or more of these sensors could control one or more actuators that, in turn, control the robots movement. Further, the sensors, actuators, and other parts of the robot can connect independently to an IP network with some centralized server that governs the overall control of the robot. Another term commonly used when discussing the Industrial IoT, and in particular, the Industrial Internet, is operation technology. Operation technology (OT) refers to the traditional hardware and software systems found within industrial environments. Some examples include programmable logic controllers (PLC), distributed control systems (DCS),

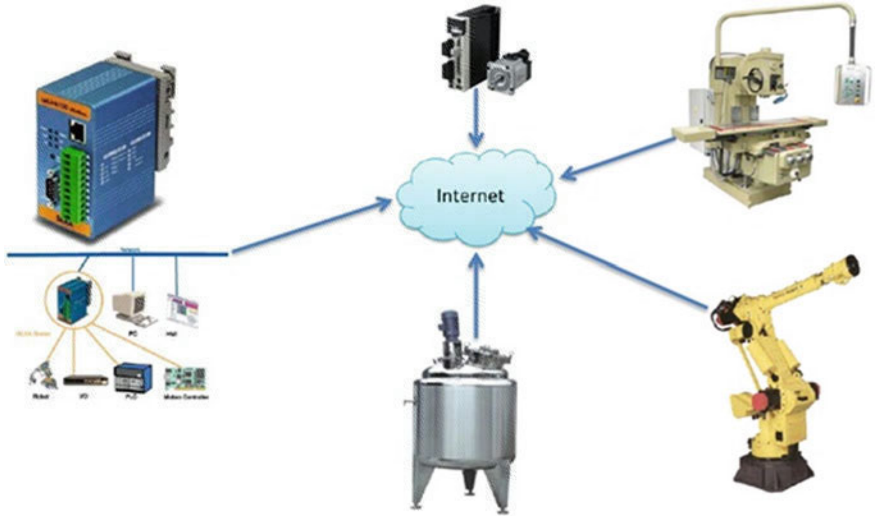

Fig. 1 Abstract idea of the industrial IoT

and human-machine interfaces (HMI). These systems are also known as Industrial Control Systems (ICS) because they control the various processes that occur within an industrial environment.

The Industrial IoT is a subset of the more general IoT. Hence, some of their characteristics are similar. The most common characteristic is that they all contain embedded computing and communication technology. These systems are largely focused on sensor technology along with the collection, transmission, and processing of sensory data. Communication is obviously a key component of the Industrial IoT. As illustrated by Fig. 2, the Industrial IoT can use both wired and wireless

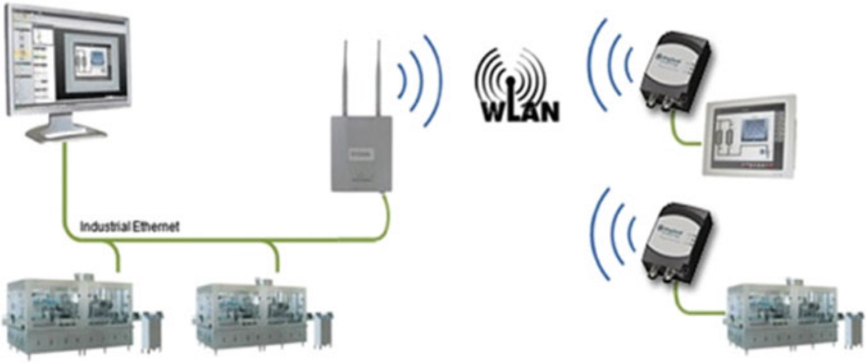

Fig. 2 An example of industrial IoT communication architecture

communication. Some of the protocols used by Industrial IoT devices include Ethernet, Wi-Fi, WiMax, LR-WPAN, 2G/3G/4G telephony, IPv4, IPv6, 6LoWPAN, HTTP, CoAP, MQTT, XMPP, DDS, and AMQP, Profinet, ModBus, and DNP. There are different protocols for different use cases, commonly driven by environmental factors and resource constraints. For example, HTTP and MQTT are application layer protocols. HTTP, the hyper-text transport protocol, is a text-based protocol commonly used by web-based systems, i.e., web servers. It is a good protocol for client-server communications when there is more of a need to do only one-way data pulling. Although multiple sets of data packets moving in both directions are required for a client to pull down a web page from a server, the protocol is designed for pure client-server architectures. However, it is common for IoT devices to act as both client and servers. In these cases, HTTP is more difficult to implement, although it can be done using a polling methodology. MQTT was designed specifically for industrial network environments. It is a publish-subscribe messaging protocol, which eases the pain in terms of two-way communications where a device might act as both a client and server. Further, it is a light weight protocol in terms of transmission overhead, and it was designed to support lossy data transmission networks.

The Industrial Internet of Things will drastically change the future, not just for industrial systems, but also for the many people involved. If we can achieve the full potential of the Industrial IoT vision, many people will have an opportunity to better their careers and standards of living because the full potential of this vision will lead to countless value creation opportunities. This always happens when new revolutions get set into motion. The full potential of the Industrial IoT will lead to smart power grids, smart healthcare, smart logistics, smart diagnostics, and numerous other smart paradigms. For example, the Industrial IoT is at the heart of a related movement called Industry 4.0. Industry 4.0 is sometimes referred to as the 4th industrial revolution, and it is a vision of smart factories built with intelligent cyber-physical systems. It will enable manufacturing ecosystems driven by smart systems that have autonomic self-* properties such as self-configuration, self-monitoring, and self-healing. This is technology that will allow us to achieve unprecedented levels of operational efficiencies and accelerated growth in productivity. New types of advanced manufacturing and industrial processes revolving around machine-to-human collaboration and symbiotic product realization will emerge. It will truly be amazing to see all of the many benefits and technological advances that can be gained if we can achieve the full potential of this technology.

The Industrial Internet of Things can have a bright and shiny future. However, the devil is in the details. The number one challenge faced by the Industrial IoT is security and privacy. Cybersecurity and data privacy issues present major hurdles and roadblocks for adopters of Industrial IoT technologies. If we cannot alleviate many of the security and privacy issues that impact the Industrial IoT, we will not be able to achieve its full potential.

2.2 New 21st Century Product Development Paradigms

The force of globalization has served to instantaneously connect people from all across the globe, bringing with it game-changing opportunities to share knowledge and expertise to benefit in a collective manner (sometimes called share-to-gain). Friedman (2005) explains that the latest globalization phase, which he coins Globalization 3.0, began around the year 2000 and was enabled by the expansion of the internet on a global basis during the dot-com boom. According to Friedman, Globalization 3.0 is defined by individuals and small groups from across the globe collaborating in areas once dominated by less-connected western economies.

Tapscott and Williams (2008) explain that the advent of the internet has led to the development of cooperative collaboration networks, resulting in a power-shift from the once mighty hierarchical business model. These traditional business models, according to the authors, can no longer sustain successful innovation: "In an age where mass collaboration can reshape an industry overnight, the old hierarchical ways of organizing work and innovation do not afford the level of agility, creativity, and connectivity that companies require to remain competitive in todays environment." Simply put, industry is going to have to rethink the traditional models of business operation, as the amount of internal expertise they hold is dwarfed by that held by the global mass of peoples connected through globalization.

In academia and industry, the Pahl and Beitzs (1988) systematic design approach and Suhs (2001) Axiomatic Design theory are two of the most widely accepted design methodologies. Pahl and Beitz describe the product development process as a series of core transformations, from problem description to requirements list, to principal solutions and working structures, to preliminary design, to detailed layouts, and to final layout, form/dimensions, and manufacturing specifications. The design activities are classified into: product planning, conceptual design, embodiment design, and detail design. Suhs Axiomatic Design is a systematic design methodology based on matrix methods to analyze the transformation of customer needs into functional requirements, design parameters, and process variables.

However, neither Pahl and Beitzs design method nor Suhs Axiomatic Design theory offers a framework that facilitates seamless information, knowledge, and resource sharing, or aids participants of global value co-creation networks in identifying potential collaboration partners or resource providers (Franke et al. 2006). For example, value can be co-created when the participants of such networks identify information, knowledge, and manufacturing resources that are more cost effective than existing ones. The motivation of the research presented in this chapter is to bridge the gap between traditional product development methods and new methods that are required in the globalized world in which paradigms such as crowd-sourcing, mass collaboration and social product development are the order of the day. We begin by giving an overview of these paradigms.

In light of a continuing globalization alluded to above, product development is not only becoming increasingly complex and dynamic but also significantly more competitive. More and more of the skills and industries that traditionally fueled the economic prosperity of our nation are becoming the commodities of today and tomorrow. In addition, new product development paradigms and associated competencies required to successfully compete in the "flat" world are emerging at a mind-boggling rate of speed. Some of these new paradigms can be considered real game changers and are worth a closer look.

Complex social networks, consisting of millions of individuals, have formed over the Internet through emerging Web 2.0 technologies such as blogs, discussion boards, wikis, and collaboration networks such as Facebook or LinkedIn, video networks such as YouTube, and countless others. Information on almost anything is readily available to everyone through the Web, anytime and anywhere. Individuals, who have never met physically, are already collaborating on the development of complex products and services for major companies, collectively solving challenging problems that are openly "crowd sourced" to a community of interested engineers, scientists, and even hobbyists. While this may sound weird to some of us, for the next generation of engineers, it will be the norm. Their number one material to work with will be information, their final product(s) will be intellectual property and innovation, and their generation is already becoming known as the generation of knowledge workers.

Globalization 3 has led to the emergence of various game-changing paradigms anticipated to foster breakthrough innovation. These paradigms are characterized by the self-organization of individuals into loose networks of peers to produce goods and services in a very tangible and ongoing way. These paradigms include, among others, crowd-sourcing, mass collaboration, and open innovation. Enabling technologies for these paradigms include first and foremost the Internet, social networking platforms for business, cloud computing, as well as new business philosophies, such as "share to gain". New organizational structures based on self-organizing communities are emerging to complement traditional hierarchies. According to Tapscott and Williams (2008), new principles for success in the globalized world are (a) openness to external ideas, (b) individuals as peers, (c) sharing of intellectual property, and (d) global action. In such emerging organizations, individual success is defined by the recognition gained through contributions towards a common goal rather than by following the directions from the top management. An organization's success is determined by its ability to integrate talents of dispersed individuals and other organizations.

Crowd sourcing is defined as "the act of sourcing tasks traditionally performed by specific individuals to a group of people or community (crowd) through an open call" (Wikipedia 2017). Because it is an open call to a group of people, it attracts those who are most fit to perform tasks or solve problems, and provide fresh and innovative ideas. This way, a significantly higher talent pool than the one any company could possibly have can be tapped. Procter & Gamble, for example, created their own platform for this, called Connect + Develop, years ago.

Closely related to crowd sourcing is the paradigm of mass collaboration. Here, the idea is to harness the intelligence and ideas of many (or the crowd), to find innovative solutions to complex problems. Mass collaboration can be defined as "a form of collective action that occurs when large numbers of people work independently on a single project, often modular in its nature. Such projects typically take place on the Internet using social software and computer-supported collaboration tools such as wiki technologies, which provide a potentially infinite hyper-textual substrate within which the collaboration may be situated" (Wikipedia 2017). While the online encyclopedia Wikipedia may be one of the most prominent examples for a mass-collaborative project, there are many other examples of projects related to the development of real world products in this fashion.

The two preceding paradigms are considered to foster Open Innovation, a term coined by Henry Chesbrough (2003). According to his definition, open innovation is "a paradigm that assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as the firms look to advance their technology". He also states that "...the central idea behind open innovation is that in a world of widely distributed knowledge, companies cannot afford to rely entirely on their own research, but should instead buy or license processes or inventions (i.e. patents) from other companies. In addition, internal inventions not being used in a firms business should be taken outside the company (e.g. through licensing, joint ventures or spin-offs)". This is closely related to what others refer to as share-to-gain. Crowd sourcing, mass collaboration and open innovation certainly have a number of appealing characteristics. However, there are two major issues that currently make companies shy away from these new paradigms. One is intellectual property (IP), which can be tricky waters to navigate, especially on a global level. The second one is a lack of new business models to go along with the new paradigms. Companies still need to make money, and while everyone will agree that putting together an online encyclopedia in a share-to-gain fashion is a neat thing to do, designing and manufacturing, for example, cars and airplanes that way isnt quite that straight forward.

The technical and enabling backbones for these new paradigms are the Web and the Internet, which has grown into a huge "supercomputer" that is continuously getting smarter, i.e., capable of responding to its semantic surroundings, for the world to share. Today, a myriad of software packages to facilitate all sorts of online collaboration, both for professional as well as personal purposes, are available. They range from simple video communication tools such as Skype to more complex collaboration suits like Wiggio, up to full-blown product design solutions, such as Dassault Systems CATIA V6 in concert with their cloud-based collaboration platform SwYm.

Cloud computing, originally conceptualized in the 1960s, is a fancy marketing term for networked computers that provide services (or resources) through the Internet to a network of clients who utilize them, usually on a pay-as-you-go cost model. The three most prominent cloud computing application areas are Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). Clouds can be public, private, or a hybrid in nature. In other words, companies may choose to implement their own internal cloud as a Local Area Network (private cloud), use the cloud-infrastructure from a third-party provider (public cloud), or opt for a hybrid for example, to rent and run software as a service in the public cloud and store application data in a local, private cloud.

Recently, cloud computing has made its advent to the domain of computer-aided product development. In addition to running CAD systems as a service in the cloud, other business-related everything-as-a-service models have started to emerge. One such model relates to manufacturing and aims at utilizing physical resources, for example, 3D printers for additive manufacturing, mills, lathes, and other manufacturing-related equipment, through the cloud. Long-term, computer-aided product development in general (including design, analysis and simulation, as well as manufacturing) is anticipated to become predominantly cloud-based. It is a promising new model to facilitate globally distributed design and manufacture processes that seamlessly integrate both virtual and physical resources. In the next section, we provide a discussion of cloud-based design and manufacturing (CBCM) that seeks to enhance the Industry 4.0 paradigm by harnessing the power of crowdsourcing, open innovation, and mass collaboration along with technologies such as cloud computing, the Internet, and the web as a new 21st Century Product Development Paradigm.

3 Cloud-Based Design and Manufacturing

Before introducing CBDM and identifying its key characteristics, we first review some of the existing definitions of cloud computing:

- Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction (NIST 2011).
- Cloud computing refers to both the applications delivered as services over the internet and the hardware and systems software in the datacenters that provide those services. The services themselves have long been referred to as Software as a Service (SaaS). The datacenter hardware and software is what we will call a Cloud (Armbrust et al. 2010).
- Clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms, and/or services). These resources can be dynamically reconfigured to adjust to a variable load (scale), allowing also for an optimum resource utilization. This pool of resources is typically exploited by a pay-per-use model in which guarantees are offered by the infrastructure provider by means of customized SLAs (Vaquero et al. 2009).
- A cloud is a type of parallel and distributed system consisting of a collection of interconnected and virtualized computers that are dynamically provisioned and presented as one or more unified computing resources based on service-level agreements established through negotiation between the service provider and consumers (Buyya et al. 2008).
- Cloud computing is both a UX and a business model. It is an emerging style of computing in which applications, data and IT resources are provided to users as services delivered over the network. It enables self-service, economies of scale

> and flexible sourcing options an infrastructure management methodology—a way of managing large numbers of highly virtualized resources, which can reside in multiple locations...(IBM 2010).

From above, a number of well-known and widely cited definitions of cloud computing are presented. Here, we put these ideas in a historical perspective in order to understand the origin of cloud computing, where it comes from, and its evolution. While the term cloud computing was only coined in 2007, the concept behind cloud computing, delivering computing resources through a global network, was rooted in 1960s (Licklider 2010). The term "Cloud" is often used as a metaphor for the Internet, and refers to both hardware and software that deliver applications as services over the Internet (Armbrust et al. 2010). When looking backward, one realizes that cloud computing is based on a set of pre-existing and well researched concepts such as utility computing, grid computing, virtualization, service oriented architecture, and software-as-a-service (Bohm 2010). One milestone is utility computing, proposed by John McCarthy in 1966. The idea of utility computing is that "computation may someday be organized as a public utility". Due to a wide range of computing related services and networked organizations, utility computing facilitates integration of IT infrastructure and services within and across virtual companies (Parkhill 1966). Another milestone is that Ian Foster and Carl Kesselman proposed the concept of grid computing in 1999. A computational grid refers to a hardware and software infrastructure that provides dependable, consistent, pervasive, and inexpensive access to high-end computational capabilities (Foster and Kesselman 1999). Since cloud and grid computing share a similar vision, Foster et al. (2008) identified the main differences between grid computing and cloud computing. The greatest difference is that cloud computing addresses Internet-scale computing problems, utilizing a large pool of computing and storing resources, whereby grid computing is aimed at large-scale computing problems by harnessing a network of resource-sharing commodity computers, dedicating resources to a single computing problem.

Compared to grid computing, we envision that cloud computing would be the most promising underlying concept that can be borrowed in the fields of design and manufacturing due to the advantages of greater flexibility, ubiquitous availability of high capacity networks, low cost computers and storage devices as well as service-oriented architecture. Thus, before exploring CBDM in more detail, it is worthwhile to take a close look at what make cloud computing unique and how it is being leveraged in design and manufacturing fields.

Cloud computing can be seen as an innovation from different perspectives. From a technical perspective, it is an advancement of computing history that evolved from calculating machines with binary digit systems, to mainframe computers with floating-point arithmetic, to personal computers with graphical user interfaces and mobility, to the Internet that offers computing resources via distributed and decentralized client-server architectures, and eventually to utility, grid, and cloud computing (Boem et al. 2010). From a business perspective, it is a breakthrough which is changing the mode of IT deployment and potentially creating new business models.

In order to leverage cloud computing in existing manufacturing business models and enterprise information systems, cloud manufacturing, based on cloud computing and service-oriented technologies, is proposed (Tao et al. 2011). The architecture, core enabling technologies, typical characteristics for cloud manufacturing, and the difference and relationship between cloud computing and cloud manufacturing has been discussed. Xu (2012) discusses the potential of cloud computing that can transform the traditional manufacturing business models by creating intelligent factory networks. Two types of cloud computing adoptions in the manufacturing sector have been suggested, direct adoption of cloud computing technology in the IT area and cloud manufacturing where distributed resources are encapsulated into cloud services and managed in a centralized manner.

4 Defining Cloud-Based Design and Manufacturing (CBDM)

Based on the concept of cloud computing, we propose a definition of CBDM as follows (Wu et al. 2012):

Cloud-Based Design and Manufacturing refers to a product realization model that enables collective open innovation and rapid product development with minimum costs through a social networking and negotiation platform between service providers and consumers. It is a type of parallel and distributed system consisting of a collection of inter-connected physical and virtualized service pools of design and manufacturing resources (e.g., parts, assemblies, CAD/CAM tools) as well as intelligent search capabilities for design and manufacturing solutions.

Figure 3 illustrates the concepts underlying the foundations and principles of CBDM systems aligned with our proposed definition thereof. At this point, it is noteworthy to explain the use of the term Cloud. Communication and network engineers have traditionally encapsulated the inherent interconnection complexity of networks with cloud diagrams. In essence, a network of any reasonable size is too complex to draw on a diagram. Consequently, cloud diagrams are used to hide the interconnect complexity while simultaneously revealing the primary details of a particular network diagram. As seen from Fig. 3, the Internet communication cloud forms the basic and required underlay network for any CBDM system in general. As stated previously, CBDM technologies are enabled by Internet-based information and communication technologies. This dependency is represented by illustrating CBDM as an overlay in Fig. 3. Moreover, Fig. 3 seeks to illustrate the overall and basic interconnectivity of the primary elements of a CBDM system. For example, the human resources of a CBDM system form their own human-centric network, which is represented by design teams, social networks, and students, just to name a few. Likewise, the cloud resources, which include human, virtual, and physical resources, are

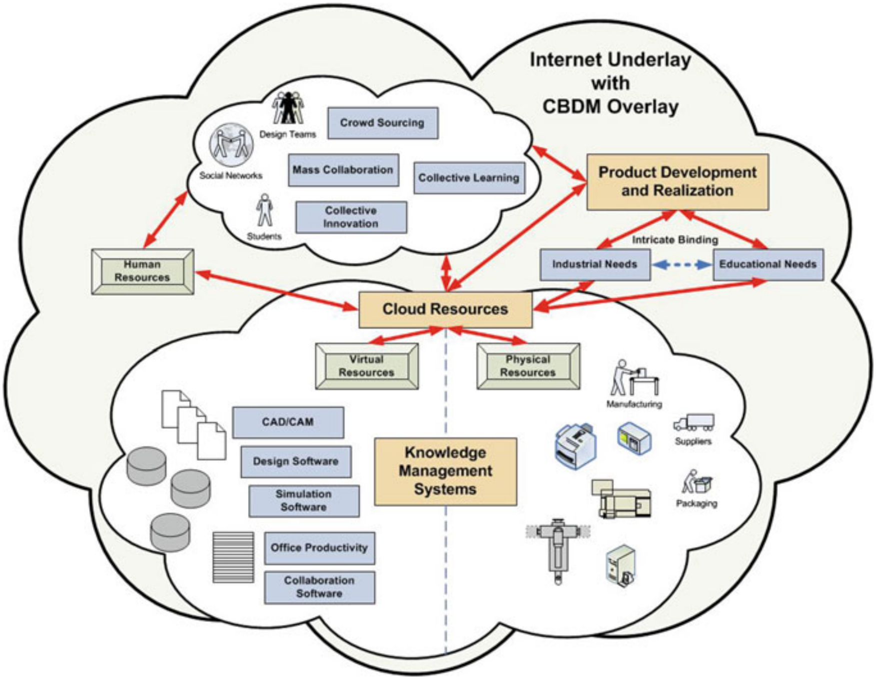

Fig. 3 The CBDM concept

illustrated along with their appropriate partitions. One of the primary goals of CBDM is to enable efficient product development and realization processes. Hence, appropriate interconnections are established between this goal and the basic partitions of the diagram. Further, one should observe the needs of the product development and realization process: namely, industrial needs and educational needs. These two sectors comprise the basic categories of entities that need the CBDM functionality. Moreover, industrial needs and educational needs are, in general, intricately bound. Industry will use CBDM technology to produce raw goods and services. Obviously, industry depends on educational entities for the following: (1) to educate students on the basic principles and foundations of CBDM systems in order to accomplish their economic goals and (2) to conduct cutting-edge research and development on the underlying details of CBDM systems. Hence, the educational and industrial entities are intricately bound.

In addition, the essential characteristics of CBDM, including on-demand self-service, ubiquitous network access, rapid scalability, resource pooling, and virtualization are emphasized as prerequisites to enable CBDM as follows:

- On-demand self-service: A customer or any other individual participating in the cloud can provide and release engineering resources, such as design software, manufacturing hardware, as needed on demand. It provides a platform and intuitive, user-friendly interfaces that allow users (e.g., designers) to interact with other users (e.g., manufacturers) on the self-service basis.

- Ubiquitous network access: There is an increasing need for a so-called customer co-creation paradigm, which enables designers to proactively interact with customers, as well as customers to share different thoughts and insights with designers. In order to easily reach such a communication media, it requires a capability of broad and global network access. The CBDM systems can provide such access to the network where cloud consumers reside through multiple tools, e.g., mobile phones and personal digital assistants. CBDM allows various stakeholders (e.g., customers, designers, managers) to participate actively throughout the entire product realization process.
- Rapid scalability: The CBDM systems allow enterprises to quickly scale up and down, where manufacturing cells, general purpose machine tools, machine components (e.g., standardized parts and assembly), material handling units, as well as personnel (e.g., designers, managers, and manufacturers) can be added, removed, and modified as needed to respond quickly to changing requirements. It helps to better handle transient demand and dynamic capacity planning under emergency situations incurred by unpredictable customer needs and reliability issues. For example, the cloud system allows the cloud service consumers to quickly search for and fully utilize resources, such as idle and/or redundant machines and hard tools, in another organization to scale up their manufacturing capacity.
- Resource pooling: The cloud providers design and manufacturing resources are pooled to serve cloud consumers in a pay-per-use fashion. Resources include engineering hardware (e.g., fixtures, molds, and material handling equipment) and software (e.g., computer-aided design and Finite Element Analysis (FEA) program packages). The CBDM model enables convenient and on demand network access to such a shared pool of configurable manufacturing resources. The real time sensor inputs, capturing the status and availability of manufacturing resources, ensures effective and efficient cloud resource allocation.
- Virtualization: The CBDM systems provide a virtual environment through the simulation of the software and/or hardware upon which other software runs. It enables enterprises to separate engineering software packages, computing and data storage resources from physical hardware, as well as to support time and resource sharing.

4.1 Cloud Based Design

Cloud Based Design (CBD) is a part of the CBDM concept with a focus on design aspects. CBD refers to a design model that leverages Web 2.0 (i.e., social network sites, wikis, online reviews, and recommender systems) and Web 3.0 to support the gathering, representation, processing, and use of product design-related information that is distributed across social media and the Internet (Wu et al. 2013).

Traditionally, it has been assumed that generating design ideas and implementing them was the exclusive task of design teams. However, CBD has the potential to enable customers, engineers, and other participants to share information through social media by integrating Web 2.0 tools into product design processes. For example, a Web 2.0 site provides service providers and consumers a vehicle to communicate and interact with each other through online product reviews. In this way, designers can easily get feedback on their customers user experience.

In addition, due to the vast amount of product design-related data in social media, engineers are facing a significant challenge in quickly find the information they need. Web 3.0 allows the information to be precisely described in terms of ontology that can be understood by machines. Web 3.0 will support effective and efficient discovery, automation, and reuse of data for CBD.

4.2 Cloud Based Manufacturing

Cloud based manufacturing (CBM) is the other part of the CBDM concept with a focus on the manufacturing aspect. CBM refers to "a customer-centric manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource loading in response to variable-demand customer generated tasking". (Wu et al. 2013) the motivation for introducing CBM is based on the belief that CBM can lead to important advances in new ways of conducting manufacturing activities from the following perspectives.

First, one of the main reasons for the adoption of CBM by manufacturing enterprises is the emerging outsourcing and crowd sourcing models in manufacturing. CBM may (1) facilitate Small and Medium-Sized Enterprises (SMEs) run manufacturing operations more cost effectively by utilizing excessive manufacturing resources owned by large enterprises; and (2) enable large sized enterprises to develop and enhance their core competencies and innovation capabilities by crowd-sourcing labor-intensive tasks.

Second, one of the distinguishing characteristics of CBM is that CBM allows enterprises to quickly scale up and down, where manufacturing cells, general purpose machine tools, machine components (e.g., standardized parts and assembly), material handling units, as well as personnel (e.g., designers, managers, and manufacturers) can be added, removed, and modified as needed to respond quickly to changing requirements.

4.3 CBDM Services

Figure 4 presents some example CBDM cloud services available to a cloud consumer.

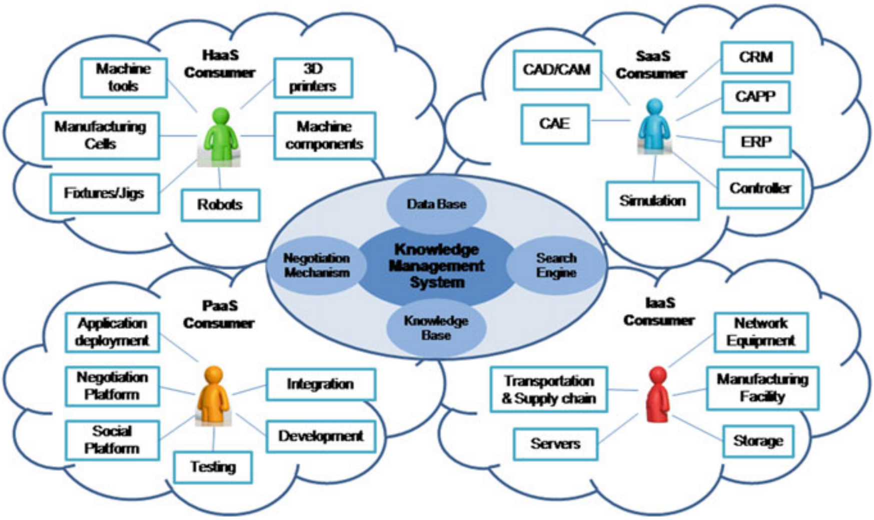

Fig. 4 CBDM example services

Hardware-as-a-Service (HaaS): HaaS delivers hardware sharing services, e.g., machine tools, hard tooling, and manufacturing processes, to cloud consumers through the CBDM system. Cloud consumers are able to rent and release hardware provided by a third party without purchasing them. The Cubify.com 3D online printing service is a good example, which allows cloud consumers to produce parts through any mobile device using their online 3D printing service without purchasing 3D printers. The consumers of HaaS could be either engineers or end users, who may utilize manufacturing hardware.

Software-as-a-Service (SaaS): SaaS delivers software applications, e.g., CAD, CAM, FEA tools, and Enterprise Resource Planning (ERP) software to cloud consumers. Cloud consumers are able to install and run engineering and enterprise software through a thin client interface without purchasing full software licenses. The cloud service offered by Dassault Systems and Autodesk are by far the best known examples among engineering analysis applications, allowing remotely running 3D software and high performance discrete computing environments (Autodesk 2017; Dassault 2017). The consumers of SaaS can be designers, engineers and managers, who need access to software applications.