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Industry 4.0: Managing The Digital Transformation

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ISSN 1860-5168 ISSN 2196-1735 (electronic)
Springer Series in Advanced Manufacturing
ISBN 978-3-319-57869-9 ISBN 978-3-319-57870-5 (eBook)
https://doi.org/10.1007/978-3-319-57870-5

Library of Congress Control Number: 2017949145

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

As a new industrial revolution, the term Industry 4.0 is one of the most popular topics among industry and academia in the world. Industry 4.0 plays a significant role in strategy to take the opportunities of digitalization of all stages of production and service systems. The fourth industrial revolution is realized by the combination of numerous physical and digital technologies such as artificial intelligence, cloud computing, adaptive robotics, augmented reality, additive manufacturing and Internet of Things (IoT). Regardless of the triggering technologies, the main purpose of industrial transformation is to increase the resource efficiency and productivity to increase the competitive power of the companies. The transformation era, which we are living in now, differs from the others in that it not only provides the change in main business processes but also reveals the concepts of smart and connected products by presenting service-driven business models.

In this context, this book is presented so as to provide a comprehensive guidance for Industry 4.0 applications. Therefore, this book not only introduces implementation aspects of Industry 4.0, but also proposes conceptual framework for Industry 4.0 with respect to its design principles. In addition, a maturity and readiness model is proposed so that the companies deciding to follow the path of digital transformation can evaluate themselves and overcome the problem of spotting the starting point. A technology roadmap is also presented to guide the managers of how to set the Industry 4.0 strategies, select the key technologies, determine the projects, construct the optimized project portfolio under risk and schedule the projects in planning horizon. Meanwhile, the reflections of digital transformation on engineering education and talent management are also discussed. Then, the book proceeds with key technological advances that form the pillars for Industry 4.0 and explores their potential technical and economic benefits via demonstrations with real-life applications.

We would like to thank all the authors for contributing to this book

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- Basar Oztaysi, Istanbul Technical University
- Sezi Cevik Onar, Istanbul Technical University

- Gokhan Ince, Istanbul Technical University
- Ihsan Kaya, Yildiz Technical University
- Erkan Isikli, Istanbul Technical University
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- Burak Aydin, Silver Spring Networks
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We would also like to thank our colleague Ceren Salkin Oner for her support to prepare the final format of the book. And finally, we thank our families for their moral support and endless patience.

Istanbul
2017

Alp Ustundag
Emre Cevikcan

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Part I
Understanding Industry 4.0

Chapter 1
A Conceptual Framework for Industry 4.0

Ceren Salkin, Mahir Oner, Alp Ustundag and Emre Cevikcan

Abstract Industrial Revolution emerged many improvements in manufacturing and service systems. Because of remarkable and rapid changes appeared in manufacturing and information technology, synergy aroused from the integration of the advancements in information technology, services and manufacturing were realized. These advancements conduced to the increasing productivity both in service systems and manufacturing environment. In recent years, manufacturing companies and service systems have been faced substantial challenges due to the necessity in the coordination and connection of disruptive concepts such as communication and networking (Industrial Internet), embedded systems (Cyber Physical Systems), adaptive robotics, cyber security, data analytics and artificial intelligence, and additive manufacturing. These advancements caused the extension of the developments in manufacturing and information technology, and these coordinated and communicative technologies are constituted to the term, Industry 4.0 which was first announced from German government as one of the key initiatives and highlights a new industrial revolution. As a result, Industry 4.0 indicates more productive systems; companies have been searching the right adaptation of this term. On the other hand, the achievement criteria and performance measurements of the transformation to Industry 4.0 are still uncertain. Additionally, a structured and systematic implementation roadmap is still not clear. Thus, in this study, the fundamental relevance between design principles and technologies is given and conceptual framework for Industry 4.0 is proposed concerning fundamentals of smart products and smart processes development.

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A. Ustundag and E. Cevikcan, *Industry 4.0: Managing The Digital Transformation*,
Springer Series in Advanced Manufacturing, https://doi.org/10.1007/978-3-319-57870-5_1

1.1 Introduction

Since first Industrial Revolution had aroused after steam engine, the following radical changes were appeared such as digital machines, automated manufacturing environment, and caused significant effects on productivity. The main reasons and triggers of the radical changes are individualization of demand, resource efficiency and short product development periods. Thus, enormous developments such as Web 2.0, Apps, Smartphones, laptops, 3D-printers appeared and this situation creates a big potential in the development of economies. Recently, in European Union, almost 17% of the GDP is explicated for by industry, which also effectuated approximately 32 million job opportunities (Qin et al. 2016). In contrast to this potential, today's companies are dealing with the challenges in rapid decision making for increasing productivity. One example could be given from the transformation process toward automated machines and services, which leads the coordination and connection of distributed complex systems. For this aim, more software-embedded systems are engaged in industrial products and systems, thereby, predictive methods should be constituted with intelligent algorithms in order to support electronic infrastructure (Lee et al. 2015).

In parallel to the necessity of coordination mechanism, synergy aroused from the integration of the advancements in information technology, services and manufacturing forms a new concept, Industry 4.0, was first declared by German government during Hannover Fair in 2011 as the beginning of the 4th industrial revolution. As explained in Bitkom, VDMA, ZVEI's report (2016), an increasing number of physical elements obtain receivers such as sensors and tags as a form of constructive technology and these elements have been connected after then the improvements seen in Internet of Things field. Additionally, electronic devices connection is conducted as a part of distributed systems to provide the accessibility of all related information in real time processing. On top of it, ability to derive the patterns from data at any time triggers more precise prediction of system behavior and provides autonomous control. All these circumstances influence the current business and manufacturing processes while new business models are being emerged. Hence, challengers for modern industrial enterprises are appeared as more complex value chains that require standardization of manufacturing and business processes and a closer relation between stakeholders.

The term, Industry 4.0 completely encounters to a wide range of concepts including increments in mechanization and automation, digitalization, networking and miniaturization (Lasi et al. 2014). Moreover, Industry 4.0 relies on the integration of dynamic value-creation networks with regard to the integration of the physical basic system and the software system with other branches and economic sectors, and also, with other industries and industry types. According to the concept of Industry 4.0, research and innovation, reference architecture, standardization and security of networked systems are the fundamentals for implementing Industry 4.0 infrastructure. This transformation can be possible by providing adequate substructures supported by sensors, machines, workplaces and information technology systems that are communicating with each other first in a single enterprise and certainly with other communicative systems. These types of systems referred as cyber physical systems and coordination between these systems are provided by Internet based protocols and standards.

As seen from the improvements in production and service management, Industry 4.0 focuses on the establishment of intelligent and communicative systems including machine-to-machine communication and human-machine interaction. Now and in the future, companies have to deal with the establishment of effective data flow management that is relied on the acquisition and assessment of data extracted from the intelligent and distributed systems interaction. The main idea of data acquisition and processing is the installation of self-control systems that enable taking the precautions before system operation suffered. Thus, companies have been searching the right adaptation of Industry 4.0.

In this respect, transformation to Industry 4.0 is based on eight foundational technology advances: adaptive robotics, data analytics and artificial intelligence (big data analytics), simulation, embedded systems, communication and networking such as Industrial Internet, cloud systems, additive manufacturing and virtualization technologies. These technologies should be supported with both basic technologies such as cyber security, sensors and actuators, RFID and RTLS technologies and mobile technologies and seven design principles named as real time data management, interoperability, virtualization, decentralization, agility, service orientation and integrated business processes (Wang and Wang 2016). These design principles and technologies enable practitioners to foresee the adaptation progress of Industry 4.0. On the other hand, a structured and systematic implementation roadmap for the transformation to Industry 4.0 is still uncertain. Thus, in this study, the fundamental relevance between design principles and supportive technologies is given and conceptual framework for Industry 4.0 is proposed concerning fundamental links between smart products and smart processes. First, supportive technologies are defined by giving specific implementation cases. In this respect, design principles are matched with the existing technologies. Besides that, a conceptual framework for a strategic roadmap of Industry 4.0 is presented, consisting of multi-layered and multi-functional steps, which is the main contribution of this study. In conclusion, future directions and possible improvements for Industry 4.0 are briefly given.

1.2 Main Concepts and Components of Industry 4.0

In recent years, Industry 4.0 has attracted great attention from both manufacturing companies and service systems. On the other hand, there is no certain definition of Industry 4.0 and naturally, there is no definite utilization of the emerging technologies to initiate the transformation of Industry 4.0. Mainly, Industry 4.0 is comprised of the integration of production facilities, supply chains and service systems to enable the establishment of value added networks. Thus, emerging technologies such as big data analytics, autonomous (adaptive) robots, cyber physical infrastructure, simulation, horizontal and vertical integration, Industrial Internet, cloud systems, additive manufacturing and augmented reality are necessary for a successful adaptation. The most important point is the widespread usage of Industrial Internet and alternative connections that ensure the networking of dispersed devices. As a consequence of the developments in Industrial Internet, in other words Industrial Internet of Things, distributed systems such as wireless sensor networks, cloud systems, embedded systems, autonomous robots and additive manufacturing have been connected to each other. Additionally, adaptive robots and cyber physical systems provide an integrated, computer-based environment that should be supported by simulation and three-dimensional (3D) visualization and printing. Above all, entire system must involve data analytics and miscellaneous coordination tools to conduct a real time decision making and autonomy for manufacturing and service processes.

While constructing the framework, network of sensors, real-time processing tools, role-based and autonomous devices are interpenetrated with each other for real-time collection of manufacturing and service system data. In order to understand the proposed framework which is addressed in this study, this section gives detailed information about supportive technologies and design principles underlined for Industry 4.0 implementation with real life cases and examples. After that, proposed framework is presented with regard to design principles and supportive technologies for acquiring context-aware operational system including smart products and smart processes.

1.2.1 State of Art

For successful system adaptation to Industry 4.0, three features should be taken into account: (1) horizontal integration via value chains, (2) vertical integration and networking of manufacturing or service systems, and (3) end to-end engineering of the overall value chain (Wang et al. 2016). Vertical integration requires the intelligent cross-linking and digitalization of business units in different hierarchal levels within the organization. Therefore, vertical integration enables preferably transformation to smart factory in a highly flexible way and provides the production of small lot sizes and more customized products with acceptable levels of profitability. For instance, smart machines create a self-automated ecosystem that can be dynamically subordinated to affect the production of different product types; and a huge amount of data is processed to operate the manufacturing processes easily. On the other hand, horizontal integration obtains entire value creation between organizations for enriching product life cycle using information systems, efficient financial management and material flow (Acatech 2015). The horizontal and vertical integration enable real time data sharing, productivity in resource allocation, coherent working business units and accurate planning which is crucial for connected devices in the term, Industry 4.0. Finally, end-to-end engineering assists product development processes by digital integration of supportive technologies considering customer requirements, product design, maintenance, and recycling (Wang et al. 2016).

1.2.2 Supportive Technologies

For successful implementation of Industry 4.0 transformation, three core and nine fundamental technologies are required to be the part of the entire system. In this section, detailed information of these supportive technologies is given for better understanding of the proposed framework.

Adaptive robotics: As a consequence of the combination of microprocessors and AI methodologies, the products, machines and services become smarter in terms of having not only the abilities of computing, communication, and control, but also having autonomy and sociality. In this regard, adaptive and flexible robots combined with the usage of artificial intelligence provide easier manufacturing of different products by recognizing the lower segments of each parts. This segmentation proposes to provide decreasing production costs, reducing production time and waiting time in operations. Additionally, adaptive robots are useful in manufacturing systems especially in design, manufacturing and assembly phases (Wittenberg 2015). For instance, assigned tasks are divided into simpler sub problems and then are constituted a set of modules in order to solve each sub problem. At the end of each sub task completion, integration of the modules to reach an optimal solution is essential. One of the sub technologies underlying adaptive robots can be given from co-evolutionary robots that are energetically autonomous and have scenario based thinking and reaction focused working principle (Wang et al. 2016).

A real life example can be given: a robot called Yumi which is created for ABB manufacturing operations. Yumi has flexible handling, parts-feeding mechanism, camera based part location detection system and state-of-the-art motion control for the adaptation of ABB production processes as reported in ABB Contact (2014). Another example can be given as Kuka KR Quantec robot that has task-distributing screws and other production material by delivering the ordered KANBAN boxes coming from the central warehouse rack. The “workerbot”, created from pi4, has a humanoid anatomy with two arms, a rotating upper body and supported by camera and image processing systems. This combined mechanism enables memory based activity identification using independent recognition of the previous positions and characteristics of production parts (VDMA 2016).

The general characteristics of these applications are given in the following:

- Networked via Ethernet or Wi-Fi for high speed data transmission
- Easy integration in existing machinery communication systems
- Optical and image processing of part positioning
- Integrated robot controller
- Memory based or case based learning mechanism.

Embedded systems (*Cyber physical infrastructure*): Embedded systems, named as Cyber-Physical Systems (CPS), can be explained as supportive technology for the organization and coordination of networking systems between its physical infrastructure and computational capabilities. In this respect, physical and digital tools should be integrated and connected with other devices in order to achieve decentralized actions. In other words, embedded systems generally integrate physical reality with respect to innovative functionalities including computing and communication infrastructure (Bagheri et al. 2015).

In general, an embedded system obtains two main functional requirements: (1) the advanced level of networking to provide both real-time data processing from the physical infrastructure and information feedback from the digital structure; and (2) intelligent data processing, decision-making and computational capability that support the physical infrastructure (Lee et al. 2015). For this purpose, embedded systems consist of RTLS technologies, sensors, actuators, controllers and networked system that data or information is being transformed and transferred from every device. In addition to that, information acquisition can be derived from data processing and data acquisition in terms of applying computational intelligence supported by learning strategies such as case based reasoning.

A specific example for embedded systems can be observed in Beckhoff maintenance tool: Process parameters (stress, productive time etc.) of mechanical components can be recorded digitally while making some adjustments such as technical experiments in online or offline platforms. In addition to that case, cyber-physical research and learning platform "CP Factory" from Festo provides educational institutions and companies with access to the technology and applications of Industry 4.0. The main part of the (physical) mechanism is supported by an intelligent module for the communication of process data—the "CPS Gate". The "CPS Gate" operates within the factory's workstations as the "backbone" module for controlling the processes. Schunk linear motor drives with each prioritized order in the assembly lines repeatedly for decentralized quality assurance and documentation of quality criteria (VDMA 2016).

The embedded systems have some properties mentioned as follows:

- Increased operational safety through the detection of safety-critical status prior to their importance level,
- Sensorless or with sensor switching condition monitoring,
- Control and monitoring using feedback loops,
- Systematical and targeted integration of storage and analysis of data directly and interactively on the local control, in private networks or in the public cloud system,
- Flexible and reconfigurable parts and machines.

Additive manufacturing: Additive manufacturing is a set of emerging technologies that produces three dimensional objects directly from digital models through an additive process, particularly by storing and joining the products with proper polymers, ceramics, or metals. In details, additive manufacturing is initiated by forming computer-aided design (CAD) and modeling that arranges a set of digital features of the product and submit descriptions of the items to industrial machines. The machines perform the transmitted descriptions as blueprints to form the item by adding material layers. The layers, which are measured in microns, are added by numerous of times until a three-dimensional object arises. Raw materials can be in the form of a liquid, powder, or sheet and are especially comprised of plastics, other polymers, metals, or ceramics (Gaub 2015). In this respect, additive manufacturing is comprised of two levels as software of obtaining 3D objects and material acquisition side.

Although barriers to the existing technology are appeared especially in production processes, there are incomparable properties using 3D printers and additive manufacturing. For instance, additive manufacturing processes outperform than conventional manufacturing mechanisms for some products including shaping initially impossible geometries such as pyramidal lattice truss structures. Obviously, printing mechanism reduces material waste by utilizing only the required materials (Ford 2014). Besides that, networked system comprised of ordering, selection of injection molding is also necessary to monitor the process variables and parameters on a particular interface. Customer requirements are also involved in the manufacturing design and necessary components for these plastic parts' manufacturing are gathered in advance. The injection molding machine encapsulates the metal blades and the information system for design features interconnects the individual design process steps with proper additive manufacturing system operations. In addition to that, a laser-marking phase is also adopted in the production line (Gaub 2015).

Real life example is aroused from ARBURG GmbH that deals with individualized high volume plastic products. An ALLROUNDER injection moulding machine and a freeformer for additive manufacturing are linked by means of a seven-axis robot to 3D plastic lettering using additive processes (VDMA 2016).

Cloud technologies: Cloud based operating is another essential topic for the contribution of networked system integration in Industry 4.0 transformation. The term "cloud" includes both cloud computing and cloud based manufacturing and design. Cloud manufacturing implies the coordinated and linked production that stands "available on-demand" manufacturing. Demand based manufacturing uses the collection of distributed manufacturing resources to create and operate reconfigurable cyber-physical manufacturing processes. Here, main purpose is enhancing efficiency by reducing product lifecycle costs, and enabling the optimal resource utilization by coping with variable-demand customer focused works (Thames and Schaefer 2017a, b). Comprehensively, cloud based design and manufacturing operations indicate integrated and collective product development models based on open innovation via social networking and crowd-sourcing platforms (Thames and Schaefer 2017a, b).

As a consequence of the advancements in cloud technologies such as decreasing amount of reaction times, manufacturing data will increasingly be practiced in the cloud systems that provide more data-driven decision making for both service and production systems (Rüßmann et al. 2015). On the other hand, according to "From Industry 4.0 to Digitizing Manufacturing" report submitted by Manufacturing Technology Center, privacy and security issues aroused from system lacks are needed to be considered and secondly, extra storage needs, payment options and physical location should be carefully decided in advance (Wu et al. 2014). At the same time, productivity increases in advance: an example is from GE Digital that proposed "Brilliant Manufacturing Suite" which uses smart analytics to evaluate operational data and factory's overall equipment effectiveness is increased by 20% or more. Besides that, M&M Software's industrial cloud service platform is based on real time data analytics and consists of a universal core system of individual web portals. The mentioned system can be remotely operated on both a PC using a browser and on mobile devices.

The requirements of cloud based processing are listed as follows:

- Data driven applications are worked on cloud-based infrastructure, and every supply chain element and user is connected through the cloud system.
- Real time data analytics for notifications and abnormalities using independent cloud database function.
- Take full advantage of big data to optimize system performance according to external and sudden changes.
- Users need a connected device to see the necessary information on cloud, and they have authorized access to available applications and data worldwide.
- Proactive application function as an automatic shift log or tool change log, perform adaptive feed control, detect collisions, monitor processes, and much more besides.

Virtualization technologies (*Virtual Reality* (*VR*) *and Augmented Reality* (*AR*)): Virtualization technologies are based on AR and VR tools that are entitled the integration of computer-supported reflection of a real-world environment with additional and valuable information (Paelke 2014). In other words, virtual information can be encompassed to real world presentation with the aim of enriching human's perception of reality with augmented objects and elements (Syberfeldt et al. 2016). For this purpose, existing VR and AR applications associate graphical interfaces with user's view of current environment. The essential role of graphical user interfaces is that users can directly affect visual representations of elements by using commands on appeared on the screen and interacts with these menus referenced by ad hoc feedbacks.

According to these purposes, visualization technologies have four functional requirements: (i) scene capturing, (ii) scene identification, (iii) scene processing, (iv) scene visualization. Thus, hardware such as handheld devices, stationary visualization systems, spatial visualization systems, head mounted displays, smart glasses and smart lenses are utilized for implementation. On the other hand, key challenges for the adaptation of visualization cases present the environment with realistic objects for better user experience, adding necessary information via meta graphics and enriching users' perception by color saturation and contrast. With this respect, approaches for visualization technologies' displays are based on three focuses: (i) video-based adaptation supported by the camera that assists augmented information, (ii) optical adaptation that user gives information by wearing a special display and (iii) projection of stated objects (Paelke 2014).

Today, visualization technologies are mainly applied in diversified fields such as video gaming, tourism and recently, this topic has started to be considered within the context of constructing quality management systems, assembly line planning and organizing logistics and supply chain actions for smart factories (Paelke 2014; Syberfeldt et al. 2016; DHL report). Specific examples can be given from BMW Connected Drive that enables navigation information and assists driver assistance systems, Q-Warrior helmet for military purposes, Liver explorer for medical practitioners and Recon Jet for leisure activities (DHL Report 2015). Particularly, AR and VR systems are adapted to computer aided quality assessment for the estimation of scale, tracking the product position and visualizing current state of the product by a graphical user interface. In shop floor implementation of visualization technologies, video based glasses (Oculus Rift), optical glasses (C wear) and Android based devices, video based tablet and spatial projector are utilized. Final example could be given for logistics, especially considering warehouse operations, transportation optimization, last mile delivery, customer services and maintenance. In this virtual world, operators can interact with machines or other devices by using them on a cyber-representation and change parameters in order to interpret the operational and maintenance instructions (Segovia et al. 2015). The most remarkable future implementation of visualization systems is the requirement of tailor made solutions for human and robot collaboration and more user-friendly devices for better experience (Rüßmann et al. 2015).

The visualization technologies have some properties mentioned as follows:

- Optimal user support through augmented reality and gamification.
- Significantly more convenient and user-friendly interface design.
- The mobile projection providing holistic and latency-free support.

Simulation: Before the application of a new paradigm, system should be tested and reflections should be carefully considered. Thus, diversified types of simulation including discrete event and 3D motion simulation can be performed in various cases to improve the product or process planning (Kühn 2006). For example, simulation can be adapted in product development, test and optimization, production process development and optimization and facility design and improvement. Another example could be given from Biegelbauer et al.'s (2004) study that handles assembly line balancing and machining planning that requires to calculate operating cycle times of robots and enables design and manufacturing concurrency.

In the perspective of Industry 4.0, simulation can be evaluated as a supportive tool to follow the reflections gathered from various parameter changes and enables the visualization in decision-making. Therefore, simulation tools can be used with other fundamental technologies of Industry 4.0. For instance, simulation based CAD integration ensures the working of multiple and dissimilar CAD systems by changing critical parameters. Additionally, simulation can reflect what-if scenarios to improve the robustness of processes. Especially for smart factories, virtual simulation enables the evaluation of autonomous planning rules in accordance with system robustness (Tideman et al. 2008).

Data Analytics and Artificial Intelligence: In consequence of the manufacturing companies start to adopt advanced information and knowledge technologies to facilitate their information flow, a huge amount of real-time data related to manufacturing is accumulated from multiple sources. The collected data which is occurred during R&D, production, operations and maintenance processes is increasing at exponential speed (Zhang et al. 2016). In particular, data integration and processing in Industry 4.0 is applied for improving an easy and highly scalable adaptation for dataflow-based performance analysis of networked machines and processes (Blanchet et al. 2014). Data appears in large volume, needed to be processed quickly and requires the combination of various data sources in diversified formats. For instance, data mining techniques have to be used where data is gathered from various sensors. This information assists the evaluation of current state and configuration of different machinery, environmental and other counterpart conditions that can affect the production as seen in smart factories. The analysis of all such data may bring significant competitive advantage to the companies that they are able to be meaningfully evaluate the entire processes (Obitko and Jirkovský 2015).

Some of the data mining approaches combined with support vector machines, decision tree algorithm, neural networks, heuristic algorithms are successfully applied for clustering classification and deep learning cases. Additionally, data mining approaches are generally combined with operation research methods including mixed integer programming and stochastic programming. For instance, data visualization problems caused by high dimensional data are especially faced in big data management and to overcome this problem, adaption of quadratic assignment problem formulations is required in advance.

Unlike data processing in relational databases, three functions should be considered in order to build big data infrastructure that can operate successfully with Industry 4.0 components: (i) Big data acquisition and integration (ii) Big data processing and storage (iii) Big data mining and knowledge discovery in database. Big data acquisition and integration phase includes data gathering from RFID readers, smart sensors and RFID tags etc. Big data processing and storage configures real time and non-real time data as a form of structured and unstructured data by cleaning, transforming and integration. Finally, big data mining is adopted by clustering, classification, association and prediction using decision trees, genetic algorithm, support vector machines and rough set theory for big data mining and knowledge discovery. Particularly, big data mining does not only necessitate a certain understanding of the right application but also requires dealing with unstructured data. Thus, huge amount of data preparation including specifying substantial variables and extracting appropriate data are conducted for making precise prediction and classification (Zhang et al. 2016).

Communication and Networking (*Industrial Internet*): Communication and networking can be described as a link between physical and distributed systems that are individually defined. Using communication tools and devices, machines can interact to achieve given targets, focus on embedding intelligent sensors in real-world environments and processes. Industrial Internet of Things (IIoT) relies