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A Categorical Framework of Manufacturing for Industry 4.0 and Beyond

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Abstract

With rapid advancements in industry, technology and applications, many concepts have emerged in manufacturing. It is generally known that the far-sighted term 'Industry 4.0' was published to highlight a new industrial revolution. Many manufacturing organizations and companies are researching this topic. However, the achievement criteria of Industry 4.0 are as yet uncertain. In addition, the technology roadmap of accomplishing Industry 4.0 is still not clear in industry nor in academia to date. This paper focuses on the fundamental conception of Industry 4.0 and the state of current manufacturing systems. It also identifies the research gaps between current manufacturing systems and Industry 4.0 requirements. The major contribution is an implementation structure of Industry 4.0, consisting of a multi-layered framework is described, and is shown how it can assist people in understanding and achieving the requirements of Industry 4.0.

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Keywords: Industry 4.0; Manufacturing systems

1. Introduction

Since the first Industrial Revolution, subsequent revolutions have resulted in radical changes in manufacturing, from water and steam powered machines to electrical and digital automated production. Manufacturing processes have become increasingly complicated, automatic and sustainable, which means people can operate machines simply, efficiently and persistently [1].Nowadays modern manufacturing plays an essential role in the word, especially in European countries. About 17% of the GDP is accounted for by industry, which also creates approximately 32 million job positions with several supplementary occupations in the European Union [2]. However, in recent years the industries of European countries are facing many problems; such as an aging population and, competition from developing countries. According to the Economic Policy Committee and the European Commission, the working age population (aged from 24 to 60) is going to reduce about 48 million (16%), while there are 58 million elder people until 2050 [3]. In 2011, the industrial value share of developing countries (such as China, India, and Brazil) was about 40% of € 6,577 billion, which had increased by 179% that in 1990. In contrast, Western European countries industrial value share had decreased by 25% from 36% of €3,451 (8% in Germany, 20% in France, and 29% in the UK). These problems drive the development of industrial technologies for reducing the labour force, shorting the developing time of the product, using resources efficiently, and so on, of which the Cyber-Physical System (CPS) and Internet of Things (IoT) are two state-of-the-art technologies advanced within the last decade.

With the development of these technologies, a new concept, Industry 4.0, was introduced by German during the Hannover Fair event in 2011, which symbolises the beginning of the 4th industrial revolution [4]. Since its first publication, many European manufacturing research organizations and companies have produced work on this topic, which emphasises that under Industry 4.0, manufacturing will consist of exchanged information and controlled machines and production units acting autonomously and intelligently in interoperable. However, researchers hold different opinions of the specific requirements of Industry 4.0 and its accomplishment, acting on their various industrial technology applications [5; 6; 7; 8; 9]. It is obvious that modern manufacturing is a generalised topic, which is elaborated in multi-fields. Therefore, the current understanding of Industry 4.0 cannot claim the principles. In addition, the manufacturing industry is desperate for a

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hierarchical procedure of technology application, which will guide people to fulfil Industry 4.0.

In this paper, relying on the current situation of manufacturing, in section 2, the core requirements and design principles in different dimensions of Industry 4.0 are realised. Then, in section 3, several current manufacturing systems are introduced for presenting the gaps between the current state of manufacturing and Industry 4.0 manufacturing. Section 4 displays a multi-level crossing framework which is created including nine types of manufacturing application that express previous, recent and future industrial implementation. Based on the recent manufacturing application, this framework shows a direction for the research step by step, which would represent a procedure to accomplish Industry 4.0.

2. Industry 4.0

The first three industrial revolutions have brought mechanisation, electricity and information technology (IT) to human manufacturing. As one of the most high-tech manufacturing countries, Germany holds many of the most sophisticated manufacturing companies and factories [10]. Furthermore, the German government provides two of three Research and Development funds to industrial development, which enables industrial technology to grow rapidly. The passive machines and robots have replaced the labour forces, which means they are controlled by a human without consciousness. In 2012, the number of industrial robots was about 273 per 1000 workers in Germany [11]. However, it is still expensive in its use of employees and additional resources required for controlling, checking, or efficient maintenance. Recently, benefitting from the Internet of things (IOT) and Cyber-Physical System (CPS), the industry-relevant items, for example, material, sensors, machines, products, supply chain, and customers, are able to be connected, which means these necessary objects are going to exchange information and control actions with each other independently and autonomously. German engineers realise that manufacturing has been developed into a new paradigm shift, so-called ‘Industry 4.0’, where products tend to control their own manufacturing processing [8]. Since then, the term of Industry 4.0 is one of the most popular manufacturing topics among industry and academia in the world and has also been considered as the fourth industrial revolution with extreme impact on manufacturing in future [12]. At almost the same time, many other industrial countries are aware of this new coming manufacturing era. In China, an industrial development plan was published in 2015, which is called ‘Made in China 2025’. Also, an industry developing plan has been made for the same purposes as the Industry 4.0 [13]. In this section, the future manufacturing vision, the ongoing industry examples, and the system architecture are displayed, according to many various researchers’ research and opinions, to infer the main concepts of Industry 4.0.

2.1. The Vision and concept of Industry 4.0

There is a basic consensus among many researchers that the industrial revisions require a long-time period of development and cover the following four aspects, considered as the future manufacturing visions:

- **Factory.** As one of the main components of Industry 4.0, the future factory is going to involve a new integrative, where not only all manufacturing resources (sensors, actuators, machines, robots, conveyors, etc.) are connected and exchange information automatically, but also the factory will become conscious and intelligent enough to predict and maintain the machines; to control the production process, and to manage the factory system. In addition, many manufacturing processes, such as product design, production planning, production engineering and production and services, are going to be simulated as modular, and then connected closely end-to-end, which means these processes are not only commanded by a decentralized system but also controlled interdependently. This kind of future factory is known as a Smart Factory [14].
- **Business.** Industry 4.0 implies a complete communication network will exist between various companies, factories, supplier, logistics, resources, customers, etc. Every section optimizes their configuration in real-time depending on the demands and status of associated sections in the network, which makes the maximum profit for all cooperatives with the limited sharing resources. In addition, the costs and pollution, raw materials, CO2 emissions, etc., will be reduced. In other words, the future business network is influenced by each cooperating section, which could achieve a self-organising status and transmit the real-time responses [12].
- **Products.** Benefitting from Industry 4.0, will be a new type of product generated in manufacturing, that of smart products. These products are embedded with sensors, identifiable components, and processors which carry information and knowledge to convey the functional guidance the customers and transmits the uses feedback to the manufacturing system. With these elements, many functions could be added to the products, for example, measuring the state of products or users, carrying this information, tracking the products, and analysing the results depending on the information. In addition, a full production information log can be embedded with product assisting product developer in optimizing the design, the prediction, and the maintenance [15].
- **Customers.** Customers will also have a lot of advantages under Industry 4.0. A new purchasing method is going to be provided to customers. It allows customers to order whatever function of products, with any number even if only one is. In addition, customers could change their order and ideas at any time during production even at the last minute with no charge. On the other hand, the benefit from the smart products enables the customer not only to know the production information of the product but also to receive the advice of utilization depending on their own behaviours [16].

Besides all of these planned visions of manufacturing, many researchers and companies have been working on Industry 4.0 in many fields around these concepts [17; 18; 19; 20]. Two typical examples show the development of the Industry 4.0; which are production line demonstration and smart products.

- **The soap plant from SmartFactoryKL.** The SmartFactoryKL was built in 2005 founded by many industrial and political organizations. This industrial research institution aims to improve manufacturing technology, which became the pioneer of Industry 4.0 after 2011. The soap plant is the first demonstration of the SmartFactoryKL, which produces a customized colour liquid soap bottle in any number. Customers can choose a different colour of liquid soap in any number, and this production plant can produce the soap without any human control. Machines, components and products are identical to tracking and controlling. This production plant is designed as an integration of various communications systems controlled by the decentralized systems. Therefore, the modular construction is considered within the system allowing every component of this production to take a defined function [21].
- **The smart vehicle.** This is a typical Cyber-Physical System combined production to represent the development of Industry 4.0. The raw data includes driver's operation, vehicles condition, driving route and destination, which is collated by various types of sensors during the vehicle's operation. The data is then uploaded into a local database which comprises of a private data centre with an outside database. The outside database is used for the information collected from outside of the vehicle, such as web society and life logs. This data is uploaded by drivers when they are stationary. In the data centre, the data is not only stored in the database but also analysed, converting it into valuable information, which includes two types of data, public data, and private data. This valuable information can address many useful notations for the drivers, such as route prediction and driving skill analysis. With this production, a data mining method is used for the route prediction, which achieves 80% prediction accuracy [22].

From each of these visions and real applications, the Industry 4.0 performances are shown with the tip of an iceberg. Therefore, some researchers are considering creating the structure to give a dissection of the Industry 4.0. '5C' architecture (Table.1) is an example for guiding the development of the Industry 4.0, depending on the Cyber-Physical system attributes. This architecture is divided into five levels, 'Connection Level', 'Conversion Level', 'Cyber Level', 'Cognition Level', and 'Configuration Level' [23].

The 'Connection Level' focuses on hardware development, which is accomplished by the sensor network and wireless communication, and the other four levels pay attention to the controlling system and software implementation. On the 'Conversion Level', the raw data is transformed into useful information by using data analysis technologies. The 'Cyber Level' controls the entire network via the CPS [24]. The 'Cognition Level' and 'Configuration Level' engage the artificial intelligence in the network, which are considered as future attributes of manufacturing [25]. Manufacturing intelligence is also the main target of many researchers who are interested in Industry 4.0, which is represented by these two levels. Comparing the attributes of these two levels and the Industry 4.0, the 'Cognition Level' is considered as a lower level of Industry 4.0, and, the 'Configuration Level' tends to reveal upper levelled features of Industry 4.0 which are regarded as the accomplishment of the Industry 4.0.

Table 1. 5C architecture for implementation of Industry 4.0.

5C architecture	Main Attribute	Main Function
V. Configuration Level	Self-configure	Intelligent Production
IV. Cognition Level	Early-aware	Predictive Maintenance
III. Cyber Level	Controllable	Automated System
II. Conversion Level	Informational	Information Discovery
I. Connection Level	Communicable	Hardware Connection

Therefore, when these various types of the idea (future visions, research examples, and implementation architecture) are merged and summarized, under the Industry 4.0, several concepts of future manufacturing have been abstracted. These concepts are the main design principles of Industry 4.0, which sums up two main design principles: interoperability, and consciousness. These two main design principles include many sub-concepts, the interoperability consists of digitalization, communication, standardization, flexibility, real-time responsibility, and customizability. The predictive maintenance, decision making, intelligent presentation, self-aware, self-optimization and self-configuration comprise the consciousness [26].

The core idea of interoperability is integration, which is also the key point of IoT and CPS. There are three types of integration of Industry 4.0, horizontal integration, end-to-end integration, and vertical integration [12]. These three types of integration represent three dimensions peer to peer, horizontal integration over the business value networks, end-to-end integration across the products chain, the vertical integration through the manufacturing system.

In addition, the other main design principle of the Industry 4.0 is consciousness. Basic on this concept, Industry 4.0 requires manufacturing to be intelligent, which discovers the knowledge, make the decisions and delivers the action independently and intelligently. These results are analysed from collecting raw data from the manufacturing networks by using cutting edge intelligent technologies. Moreover, these two main design principles are cooperative to achieve Industry 4.0. The interoperability set up several connected networks as the reliable environment of Industry 4.0, the consciousness offers the Industry 4.0 the essence with the artificial intelligent functions.

3. RESEARCH GAPS BETWEEN CURRENT MANUFACTURING SYSTEMS AND INDUSTRY 4.0

The manufacturing system is an integration between equipment and labour resources, which can carry out one or more production action from the material, part or set of parts. The manufacturing system is influenced by many different factors, which are 'types of operations', 'number of workstations', 'automation level', and 'system flexibility'. Based on these factors, six general types of a manufacturing system are defined as 'single-station manned cells', 'single-station automated cells', 'manual assembly system', 'automated assembly system', 'cellular manufacturing system' and 'flexible manufacturing system' [27]. Besides these six typical manufacturing systems, there are many other manufacturing systems defined by engineers, such as computer-integrated manufacturing system, reconfigurable manufacturing system, etc. With these fundamental manufacturing systems, the Industry 4.0 has been conceived.

- **Single-station automated cells.** In contrast to the manned cell, the automated cell is fully automated. The machines used are not attended by any workers during more than one machine cycle. The labour cost has decreased, and, productivity has increased compared with the manned cell. However, this system also targets on constant product batches. A typical single-station automated cell is made up of one or more automated machine (a machine cluster) and an automated loading and unloading system, such as robots, conveyors, etc. The CNC machine centre system is a common example of this system, which can change the tool, position the product and change the pallet automatically. It can work with a loading robot or feeding system to load or unload the products [28].
- **Automated assembly system.** Increased manufacturing production has been built in the assembly automation. Compared to the manual assembly system, this system uses a handling system (usually industrial robots) to replace the workers' jobs. A fully automated assembly system is fixed, which is designed to carry out a fixed order of assembly schedule on a specific product. It requires the system to be highly stable without changing the product design during production, which means the components of the system are limited. However, this system undertakes very high product demand, normally considered in the millions. The components of the system are similar to those of the manual system, but with two important parts replacing workers, the handling system and the feeding system. In addition, the control includes sequence control, safety monitoring, and quality control which is also automated. Depending on the special requirement, the application of this system is not many as the manual system. One of the most common applications of automated assembly systems is in the machining of sheet metal forming and cutting, rolling mill operations, spot welding, plating operation, etc. [27].
- **Flexible manufacturing system.** The flexible manufacturing system is a highly automated application of 'group technology', of which flexibility is the core feature. However, a flexible manufacturing system is designed for a specific part family, which is not completely flexible. In this system, several workstations are connected to an automated transport feeder system, controlled by a distributed computer system. Every workpiece is identified during the entire production cycle, which is able to change the processing immediately. Therefore, in this system, the machine, and material utilization is increasingly improved with a small number of employees and system space, which also reduces the inventory requirements. In addition, with the high flexibility, the system can make the quick responsiveness needed for the changeover. With the advancement of the flexible manufacturing system, machining application, such as the milling and drilling operations, benefit the most [29].
- **Computer-integrated manufacturing system.** The computer-integrated manufacturing system was firstly claimed in 1973 by Joseph Harrington. However, it did not attract engineers' attention until 1984 when the computer and automated system began to be developed in manufacturing. The computer-integrated manufacturing system is a completely automated manufacturing, where the computers control all functions. An ideal computer-integrated manufacturing system implies the factory level automation from design, materials management to the production line and distribution. In addition, the simplest system is required at least two integrated computers that exchange the information. In this system, the production can response rapidly with less error. Also, the most important capability of this system is cooperative automation [30].
- **Reconfigurable manufacturing system.** The reconfigurable manufacturing system is designed for adjusting the abrupt changes of the market or another requirement within the same part family. This system tends to claim six capabilities: modularity, integrability customization, convertibility, scalability and diagnosability. However, a typical reconfigurable manufacturing system does not need to achieve all of these capabilities, and, the current applications of the system have achieved several of these characteristics. The typical system requires the CNC machines, reconfigurable machine tools, reconfigurable inspections machines and material transport system. Additionally, this system is different with the flexible manufacturing system. The flexible manufacturing system focuses on the expanding the producing range of the system. The reconfigurable manufacturing system aim at increasing the changing response of different requirement or situation, which means this system play more attention on the customized flexibility rather than production flexibility [31].

Analysing the current manufacturing system, and comparing them with the concepts of the Industry 4.0, Fig.1 can represent the 'gap' between current manufacturing systems and the Industry 4.0. In this figure, only the recently automated manufacturing systems (single-station automated cell, automated assembly system, flexible manufacturing system, computer-integrated manufacturing system and reconfigurable manufacturing system) are involved because the Industry 4.0 is discussed on the digital level manufacturing [17]. In addition, this figure only reflects the general characteristics of the manufacturing system. Some special examples of manufacturing system may have more concepts, which are not included in this figure.

According to the Fig. 1, it is obvious that the current manufacturing has not achieved Industry 4.0 level comprehensively although many researchers and companies are working on this topic. Every current manufacturing system is able to cover some of the Industry 4.0 concepts, mainly is concentrated in interoperability. The single-station automated cell is digital and connected to achieve the capability of flexibility. The current automated assembly system hardly becomes standardized, which is accomplished by the computer-integrated manufacturing system. For the flexible manufacturing system and reconfigurable manufacturing system, customers can order almost products depending their own ideas. However, the current flexible manufacturing system has not become real-time response. However, as the most advanced system, the flexible manufacturing system, and the Reconfigurable manufacturing system are closest to Industry 4.0 [32]. Therefore, from the Fig. 1, most of the systems are hard to achieve concepts of the intelligent that are the main research aim of the Industry 4.0 development neither Industry 4.0 lower or upper. These concepts of research gap are the main developing direction of the Industry 4.0 research.

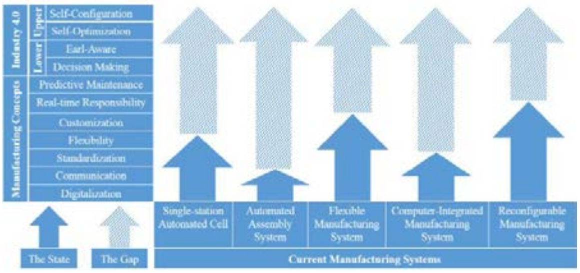

Fig. 1. Research gap between current manufacturing systems and Industry 4.0.

There is still a long way to go to improve manufacturing up to the required level to match all concepts with all dimensions, especially consciousness, which is the main aim and objective of this research. Moreover, industry and academia demand a complete structure of these technology applications to show the development of manufacturing with the different levels of performance, which will be introduced in section 4 as a framework.

4. A Categorical Framework of Manufacturing for Industry 4.0 and Beyond

The reviews of enabling technologies show the intelligence of these technologies is different, so they can be classified by levels of intelligence from low-intelligence to high-intelligence which is: Control level, Integration level, and Intelligence level [33]. On the automation level, the technologies, like computer numeric controlling, the programmable logic controlling, and probability statistics analysis etc., are used for replacing the labour force and optimizing the production efficiency. On the integration level, IoT and CPS technology are going to be applied in manufacturing based on the control level technologies, generating the digital manufacturing environment and networks. It does not only connect the hardware but also builds the communication between the controlling systems. The data is collected from sensors, machines, production lines, or manufacturing controlling and management systems, and it is also received from outside of the factory, such as the customer feedback and the supply chain. On this level more valuable information is discovered, which helps people to improve manufacturing. On the intelligence level, the manufacturing uses data or information obtained from the integration level to create the plan and make decisions by intelligent technologies, such as advanced data mining and big data analysis. In addition, the intelligent manufacturing system can self-aware, self-optimization, self-configuration, etc., which are the concepts of Industry 4.0. Applications of this level tend to be the implementation of Industry 4.0 [34].

Technology reviews alone is not enough to understand the performance of technology application. It is necessary to have categorical acting targets. In this research, the production system is discussed as the range of technology acting targets, although, the modern industry includes not only production system which acts in the factory, such as machines, robots, production process, and the factory system, but also other features; customers, logistics, and resources.

There are various reasons why the production system is the target range of this research. Firstly, the production system is the core section of the industry, including the entire products value chain from products design to services. The other section is set as the assisted part to improve the production system. Secondly, the production system is the most associated with engineering, to which it is easy to apply the technologies. Finally, the results are convenient to test. The effectiveness, yield and cost of production are measured simply and accurately in the production system. Therefore, with different levels of transparency and automation, the production system can be divided into three automation levels which are machine , production process, and factory system [35].

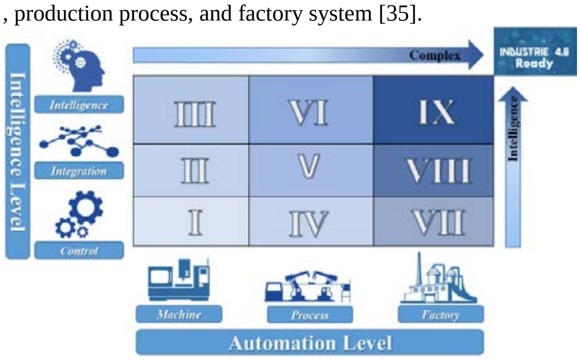

Fig. 2. A categorical framework of manufacturing for Industry 4.0 and beyond

Combining the intelligence level with the engineering level, a hierarchical framework (Fig. 2) is generated with a total of nine intelligence applications, with three intelligence level technologies acting on the three engineering level sections. These nine applications go from low-intelligence and simple automation to high-intelligence and complicated-automation.

From applications I to IX, the production system becomes increasingly automated, flexible, and intelligent. It is necessary to know that the high-level acting targets and technologies are based on the low level, which means this framework works in sequence. For example, on the factory system level, the intelligence technology is based on integration technology which is built on the automation technology. Also, on the integration technology level, the application of the factory system is based on production processing which consists of machines. In addition, application IX is defined as intelligence technology acting in a factory system. Such a factory offers several advantages such as predictive maintenance, early aware etc. The application IX is also considered as the implementation of Smart Factory by some researchers, which is a typical implantation of lower Industry 4.0 [23]. It means the upper Industry 4.0 require more intelligent technologies applied on wider manufacturing range. Moreover, the application VII and VIII can also represent examples of Industry 4.0, which are the intelligence level applications. This framework only involves the applications of production in the factory range and lower intelligent technologies, where the Industry 4.0 'ready' is beyond it. However, it draws a development roadmap for accomplishing Industry 4.0.

5. Conclusion

This paper focuses on the improvement of Industry 4.0 in a production system, and introduces the common opinions of Industry 4.0 and manufacturing. Summarizing various perspectives, the main concepts of future manufacturing has been identified to inform the research aim. In common with the entire industry, there is a huge gap between recent industry and the achievement of Industry 4.0, which has been clearly identified in this paper. In addition, a framework of Industry 4.0 is presented, which identifies how different intelligence level technologies are acted within three automation of production systems. From the framework, it is obvious that the future of current manufacturing is developing in the direction of Industry 4.0.

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