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Digitalization and intelligentization of manufacturing industry

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1 Relying on innovation to realize the historical leap

China has entered a new historical period in her development. In order to achieve scientific development and to accelerate transformation of economic development pattern, the most fundamental issue is to rely on the power of science and technology, and the most crucial element is to improve the capability of independent innovation. The key for promoting China's economic and social development is to embark on the innovation-driven track as soon as possible.

Since the 2008 global financial crisis, the landscape of the global competition has undergone profound changes. On the one hand, the strategic significance of the industrial economy has once again become prominent, as major developed countries are refocusing on the industrial economy and implementing a strategy of re-industrialization. In 2009, the U.S. enacted the *Framework for Revitalization of U.S. Manufacturing Industry* and Congress passed the *Manufacturing Promotion Act*. In late 2011, the U.S. initiated the "Advanced Manufacturing Partnership Plan" and released a five-year plan to revitalize and double the exports of the manufacturing sector. In February this year, the U.S. again promulgated an *Advanced Manufacturing National Strategic Plan*, under which she proposed to once again recognize the status of the advanced manufacturing sector in the national economy and maintain international leadership and dominance in the field of advanced manufacturing. Germany, Britain, Japan and other developed countries have launched a series of major initiatives to revitalize their manufacturing sector. On the other hand, a new round of industrial revolution is deepening, and developed countries in the West are proposing new ways of revitalizing their manufacturing sector, by relying on scientific and technological innovation, seizing the commanding heights in international industrial competition, and enhancing their core competencies in economic development in order to seize the initiative in future development. For example, through product model innovation, integration and incorporation of the latest technologies, Apple has successfully pioneered the development direction for IT products. Another example is the breakthrough of shale gas development in U.S. which brought about a "shale gas revolution". It had a profound impact not only on the world's energy situation but also on the political and economic development.

Recently, scholars in the U.S. have published a number of articles. Firstly, they emphasized the impending round of industrial revolution with "digitalization in manufacturing" as its core technology. Secondly, their viewpoint was that the U.S. had substantial advantage in information technology which should be vigorously developed and widely applied using digitalization and intelligentization as the core technology in advanced manufacturing, in order to achieve revolutionary changes in the manufacturing sector. Thirdly, they pointedly noted that with the emerging technologies, in 20 years' time China's manufacturing industry will very likely experience the budding difficulties faced by the U.S. during the past 20 years. Very soon it will be China's turn to be worried.

After 60-plus years endeavors made after the founding of New China—in particular the struggles during economic reform and opening up over the past 30 years—China's manufacturing industry has achieved historical leaps and

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bounds. Today her manufacturing GDP is ranked number one in the world. Our country has become a "Manufacturing Nation". However, we are yet to be the "Manufacturing Powerhouse". The main disparity lies in the poor product quality and our weak ability in innovation. We are always in the state of following and catching up in terms of technology, in particular we are far from mastering crucial technology, we are still at the low-end of the international division of labor and industry chain, and we are extremely weak in terms of overall competence in manufacturing.

It must be emphasized that we have full confidence in the future of China's manufacturing industry. At the same time, China's manufacturing industry is facing unprecedented challenges and opportunities. Over the next 20 years, it will be a great opportunity for China's manufacturing industry to be transformed from large to strong, and be counted among the top ranks in the world in terms of innovation and competitiveness. China's manufacturing industry possesses the following excellent conditions to enable it to achieve a breakthrough: (1) China's manufacturing industry possesses a huge domestic market, and demand is the most powerful driving force for development; (2) China's manufacturing industry has the most comprehensive system in the world with a strong industrial base; (3) China has always insisted on integrated development of formatization and industrialization, and has mastered the core technology in manufacturing digitalization with a strong technology base; (4) In relation to the development of talents in the manufacturing industry, China has a unique advantage in terms of human resources; (5) China's manufacturing industry has made outstanding achievements in innovation in areas such as aerospace, mining, maritime, high-speed rail, power transmission, power generation, and defense weaponry. It clearly shows a huge potential for innovation.

We are well aware that, compared with the U.S., there remains a significant gap in innovation between our virtual economies. Proprietary innovation in information technology lags far behind in comparison with companies such as Microsoft, Intel, Google and Apple. Nevertheless, over the next 20 years in relation to core technology for "Digitalization and Intelligentization of Manufacturing Industry", China's manufacturing industry is fully capable of achieving strategic breakthroughs, perhaps even to the extent of catching up with and even surpassing the most developed Western countries. This is a major strategic choice, and one in which China will secure great victory.

In summary, we want to promote China's manufacturing industry towards one that is innovation-driven, in order to achieve within the next 20 years, leap forward development of our country from a "Manufacturing Nation" to a "Manufacturing Powerhouse".

2 "Manufacturing digitalization and intelligentization" is the core technology of the new industrial revolution

Innovation in advanced manufacturing technology includes product innovation, manufacturing technology innovation and industry model innovation. Digitalization and intelligentization are the generic enabling technologies for product innovation and manufacturing technology innovation. They profoundly reform the mode of production in manufacturing sector as well as its shape and form. They are the core technologies for the new industrial revolution.

2.1 Product innovation: "numerical control generation" and "intelligent generation" mechanical products

2.1.1 Examination of the critical importance of product innovation through two case studies

Example 1: Digital camera

It uses the photoelectric converter to replace the traditional film and transforms the optical information into electrical information; it then digitizes and stores the information. It is a model of innovation in the application of digital technology on traditional products.

Kodak Company, which monopolized the global film industry, had developed the world's first digital camera as early as in 1975. Owing to blunders in its strategic decision-making, it did not transform the technological innovation achievements into market-oriented products. With the traditional film industry being subverted by digital technology, Kodak eventually declared bankruptcy this year.

Example 2: 3D (three-dimensional) printer

One of China's top ten scientific and technological advances in 2011 is the successful development of the world's largest 3D printer. 3D printing adopts the use of layer manufacturing with adding of additional material to generate 3D entity.

In contrast with traditional cutting of the materials, 3D printing uses adding of materials—a major innovation. 3D printer is a new type of processing equipment, and is the combined result of innovation in manufacturing process principle and innovation in digital technology products. It has the potential to change the landscape of the entire manufacturing industry.

From the two cases above, it can be seen that product innovation is extremely important to an enterprise or even to the entire manufacturing industry. The concept of "30 % product, 70 % market" is now outdated, perhaps the "70 % product, 30 % market" concept is more appropriate for today's market environment given its intense competition.

2.1.2 *Application of numerical control (NC) technology and artificial intelligent (AI) technology to achieve mechanical product innovation*

Traditional mechanical product includes three parts: the power unit, the transmission device and the working device. Although there could be a variety of approaches to innovation, there are two main ways: Firstly, innovation in the working principle or put another way, the working device, and secondly innovation in the power unit and the transmission device.

The first type of innovation, that of working principles, is a fundamental and extremely important one. One such example is the 3D printer technology. For hundreds of years mankind has been assiduously creating all types of new machines. The result is thousands upon thousands of mechanical products that are adapted for accomplishing all sorts of tasks.

Achieving mechanical product innovation through applied NC and AI technology is the second type of innovation.

Numerical control is an effective innovation of mechanical products. Its core technologies involve the replacement of power unit and transmission device in traditional machinery with the servo-motor driving system, thus enabling the total elimination or simplification of traditional mechanical transmission mechanism. It also significantly enhances the ability to control mechanical products' movement and tracking process. At the same time—and this is most important—the use of computerized control system to control the machinery's movement and work process is akin to adding a "brain" to it, enabling the machine to possess multiple functions, high level of flexibility, high precision, high performance, great reliability and ease in operation. It also makes intelligentization possible.

Numerical control is a generic common enabling technology for mechanical products. It is an integration of advanced information technology, automatic control and mechanical manufacturing technology. At its heart is digitization. The application of numerical control has caused fundamental change to the implication of using mechanical products. It enriches product functions and creates substantive changes in their performance. As such it enhances the standards as well as the market competitiveness of products. Ultimately it will lead to smart mechanical products.

Many people would automatically associate with computer numerical control (CNC) machine tools at the mere mention of numerical control. This is correct, but only up to a point. CNC machine tools are a classic example of the innovative application of numerical control on mechanical tools. Yet as it is a generic enabling technology, numerical control is capable of enabling innovation and upgrading of all types of mechanical products.

Example 3: Numerical control and intelligentization of injection molding machine

Injection molding is the most effective means for plastic molding. China is the world's largest manufacturing nation for injection molding machine and makes up more than 70 % of the world's total annual product. However she is still a long way below advanced levels with respect to the production of high-end products.

Injection molding machines need to accomplish 6 different actions, namely opening and closing of moulds, injection, plasticizing, demoulding, moulding-adjustment and movement of injection station. These are achieved by using 6 actuating mechanisms. Injection molding machines have evolved from using traditional hydraulic mechanisms to servo energy-saving mechanism. They are currently moving towards intelligent numerical control.

(i) Traditional hydraulic injection molding machine. Powered by ordinary electric motors, the transmission power unit drives 6 actuating mechanisms. It suffers from high energy-consumption, low precision, low efficiency, and considerable environmental pollution.
(ii) Energy-saving numerical control injection molding machine. It is a clever use of numerical control technology with AC servo motor replacing ordinary electric motors, while the hydraulic transmission system is retained. It is capable of supplying the required energy, and as such can save 40 %–80 % of the power consumed.
(iii) All-electric numerical control injection molding machine. It involves the full use of digital technology, with all the actuating mechanisms being powered by the servo motor and controlled by the computer's numerical control system. Its features are: high level of precision and stability, high quality of processing; ability to accomplish complex overlapping actions simultaneously; high productivity; saves power consumption by 40 %–80 %; and low noise and no oil pollution.
(iv) Intelligent CNC injection molding machine. Further introduction of intelligent technology to achieve automatic optimization of process; automatic compensation of parameters; automatic sorting of products; automatic monitoring of process and automatic diagnosis of malfunctions, thus achieving even better productivity, precision and energy-saving effects.

Example 4: Numerical control and intelligentization of locomotives

China is now one of the most developed nations for high-speed locomotive technology. Rail transportation has evolved from steam-engine locomotive, internal-combustion engine locomotive, electric locomotive to Train Set with Power Car, and is moving towards intelligentization.

(i) Steam-engine locomotive. This is driven by the coal-powered steam engine. The wheels are made to turn using linkage and rocker transmission. Centrifugal governor and air throttle are used to regulate its speed.
(ii) Internal-combustion engine locomotive. This is powered by the diesel engine. The engine provides the power to generate the electric motor which in turn powers the locomotive's wheels after rectifying and inverting the electric current. At the same time, the locomotive's movement, speed and braking are controlled by the electric transmission system.
(iii) Electric locomotive. This is directly powered by electricity which is transmitted through the contact grid to the traction transformer. The electricity is used to drive the motor after a series of step-down, variable flow, rectifying and inverting. The motor in turn drives the wheel set. Speed is controlled by way of controlling the torque output through AC with variable voltage and frequency transmitted by the traction motor. Compared with the internal-combustion engine locomotive, the electric locomotive possesses advantages such as large power output, high-efficiency power usage, no pollution and good working environment, etc.
(iv) Train set with power car. This is the digital version of the electric locomotive. Like its predecessor, power is transmitted via the electric grid to several traction transformers of Train Set with Power Car and is then treated to drive its motor which in turn drives the wheel set. The difference is that electric motors are distributed on a number of trains and powered digitally, hence the significant reduction in size. The electric motor train uses TCN grid which meets IEC61375-1 standard, and is controlled digitally.
(v) Intelligentization of electric locomotive. Intelligentization of electric locomotive is achieved by way of technologies such as data collection, network communication, intelligent decision-making and evaluation and service-oriented structures. Intelligentization will allow the electric locomotive to possess features such as self-sensing, self-learning and self-decision making, thus enabling it to provide safer and more comfortable services.

As one takes an overall view of the history of adjustments in global industrial structure and upgrading in mechanical products, one would realize that the steam engine technology allowed the machinery industry to move from manual production to mechanical production. Electrical technology in turn enabled the machinery industry to be transformed from mechanical production to electrical production. At present numerical control technology is poised to cause the industry to make a great leap from electric era to the digital era. In the foreseeable future, intelligent technology will once again enable the industry to be transformed into an "intelligentized" era. In all the above processes, we can see typical examples of generic enabling technologies.

The emergence of the "first steam-engine generation" mechanical products has brought about a power revolution through the steam engine for genetic enabling technologies. Another revolution was brought about by "first-generation electrically-driven" mechanical products, also because of its common enabling. The revolution brought about by numerical control is even more thorough as numerical control mechanical products were added with a "brain". This caused a substantive leap in the functions and performance of mechanical products. It also laid the foundation for advanced information technology such as artificial intelligence, making intelligentization the ultimate possibility.

It can be said that "first-generation numerical control" mechanical products and "first-generation intelligent" mechanical products are the products of in-depth integration of information technology and industrialization. In substance it is a deep revolution in information technology.

It can be seen that the process towards numerical control and intelligentization of mechanical products possess obvious characteristics. Both are the necessary results of substantive changes and can be applied to innovation of all types of mechanical products, thus enabling them to be upgraded and updated. They in turn completely change the landscape of mechanical industry. These are the origin and basis on which we put forward the concept of "first-generation numerical control" and "first-generation intelligentization".

2.1.3 Innovation of "numerical control generation" mechanical products

The technical path for the application of numerical control technology and intelligent technology in relation to innovation of mechanical products is clear and the technology is relatively mature and reliable. Numerical control is suitable for comprehensive innovation of mechanical products of all types of industries. They include metal processing equipments (in particular metal-cutting machine tool); non-metal processing equipments (such as plastic processing machinery); equipments for manufacturing of food, drinks, agricultural by-products, household chemicals and pharmaceuticals; transportation equipments such as automobiles, trains, aircrafts and ships; military equipments such as guns, radar and tanks, and engineering, agricultural, construction, port, printing and medical equipments, etc.

First, numerical control can be widely used for upgrading and updating of low- to mid-range mechanical

products to significantly raise their performance and market competitiveness, as well as improve productivity and quality of the manufacturing industy. CNC braiding machine is one such example.

Example 5: CNC braiding machine

China is a major nation in wool and textile weaving. Dalang Town in the city of Dongguan alone produces more than 300 million pieces of sweaters annually. At present, local manufacturers of sweaters mainly rely on the manual braiding machine. As such they suffer from low productivity and intensive labor effect. At one time there were as many as 500,000 workers from the rural regions in Dalang Town who were engaged in braiding and weaving work.

The speed of a single NC braiding machine is 5–8 times faster than that of the manual knitting machine. In addition, each worker can operate 5 machines simultaneously. This is an enormous increase in productivity. If integrated with CAD/CAM system for design of sweaters, it would significantly increase the range of color and quality of sweaters, as well as their market competitiveness.

Second, the electric automotive is another classic example of numerical control mechanical products. In recent years the US military has been developing advanced weapons such as "electric tank", "electric aircraft" and "electric ships". In substance they are electrically-powered and numerically controlled digital equipments. China's "Marine Oil 981" platform is also a classic example of fully-electric marine engineering platform.

Example 6: "Marine Oil 981" platform

Power is generated by diesel engines and is used to drive the entire platform which is numerically controlled. For an engineering complex of such immensity to be able to withstand the wind and the waves, the secret lies in its 8 electrically-powered propellers. Controlled by the computer system, the propellers can make adjustments in their driving angle and force, thus ensuring the stability of the marine oil platform.

Last but not least, numerical control enables the mechanical equipment to possess a "brain". It opens up a vast new area for innovation of high-end machinery. Developing the precision photo-etching worktable is one such example.

Example 7: Precision photo-etching worktable

The photo-etching machine is the most important, complex and expensive equipment in IC manufacturing. Given its importance as a key device for the photo- etching machine, the super-precision worktable has an extraordinary demand for precision—almost to physical limits—something that ordinary mechanical workmanship cannot achieve.

In order to achieve high speed, large displacement and nano-level precision movement with six degrees of freedom, the key in addition to acceptable movement structure and precision inspection technology, lies in digital control. At its core is digital compensation. By way of compensation control, the 100 nm photo-etching worktable developed exclusively in China is able to meet the technical requirements for high speed and high precision.

As information technology, sensing technology, control technology and artificial intelligence technology continue to be developed and applied so as to achieve real-time detection, treatment, compensation and control of mechanical products' work status and environment for mechanical products, there is sure to be continuous improvement in the capability of self-adaptation, self-learning and self-decision making of NC mechanical products. This will enable "first-generation numerical control" mechanical products to further evolve to "first-generation intelligent" mechanical products.

2.2 Innovation in manufacturing technology: digitized and intelligent integrated manufacturing technology

Digitization and intelligentization will not only achieve innovation in mechanical products, but also achieve innovation in manufacturing technologies as generic technologies, developing the manufacturing industry towards integration of digitalization and intelligentization, thereby raising the level of product design, processing and management.

2.2.1 Innovation in design technology

It is possible to carry out the parallel and synergistic fully-digital design through the use of the digital intelligent design system that encompasses the product's full life cycle and that possesses rich design database and is supported by simulation technology along with virtual reality, computer network and database support. Simulation of structure, performance and functions is optimized to be realistic, thus enhancing the product's design quality and success rate for one-time development.

Example 8: Fully-digital design of Boeing 777/787 and ARJ21 aircrafts

Design of Boeing 777/787 is fully digital including that for full aircraft, parts testing and assembly of aircraft. All development and testing are carried out in parallel at different locations and departments; virtual reality technology is used to carry out simulated flight under all types of conditions. The technology has made it possible to achieve joining of the aircraft with its wings in only one attempt as well as success at its maiden flight. The development cycle is shortened by 40 % and re-work amount is reduced by 50 %.

Development of ARJ21 aircraft in China also adopts full 3D digital design technology and parallel engineering, with successful joining of the main parts at the first attempt and success during the aircraft's maiden flight.

2.2.2 Innovation in processing technology

The first innovation involves that of manufacturing process technique. Digital technology has not merely spurred major innovations in processing principle (an example is the material and processing technique for 3D printing as mentioned above). Significant improvement in the precision level and productivity of all types of manufacturing techniques—and hence the level of workmanship for the entire manufacturing industry—is made possible with full application of digital and intelligent technologies such as simulation optimization, digital control, real-time testing of status information and self-adaptation control, etc. Below is one such example.

Example 9: Direction solidification of single crystal blade for aircraft engines

The engine is the heart of an aircraft. It is for this reason that the first batch of engines for our nation's C919 aircraft had to rely on advanced foreign technologies.

Of the various parts of an aircraft engine, the most important parts are heating parts that are subject to extreme temperature, for which high-temperature alloy materials and their manufacturing technique hold the key. Indeed engine blades have evolved from axial crystal blade to directional columnar crystal blade to directional single crystal blade that is used today. High-temperature alloy single crystal blade is manufactured using vacuum melting, vacuum casting and directional solidification. During the process of directional solidification for aviation single crystal blades, optimized modeling simulation for the microstructures is enhanced by digital technology to carry out precision control. The result is enhanced quality and rate of finished product for single crystal blades.

The second innovation involves that of manufacturing equipments and systems. Digital and intelligent technologies have enabled rapid development of CAD, CAM, CAPP and digital production and installation, thus significantly enhancing the functionality, performance and level of automation for the production system. At the same time, integration of such technologies enables the formation of flexible manufacturing cell, digital factory floor and even digital factory. This has the effect of continuous enhancement of the production system's level of flexible automation, as well as allows it to be developed into intelligent production system characterized by awareness, decision-making and execution.

2.2.3 Innovation in management technique

The objective of management is to seek optimization of the product life cycle and even the company's overall layout, as well as its best operating model. Integration and application of digital and intelligent technologies will allow the formation of the computerized integration production system, the integrated intelligent product system and even the digitized corporation. They will enable the corporation to have centralized management of all the data for a product throughout its entire life cycle. They will also enable the corporation to have integrated management of all its resources. Through integration of information from supply decision-making to its internal departments and then to its users, the corporation's speed of market response and product development can be significantly improved.

What needs to be emphasized is that manufacturing industry referred to above also includes dispersed-type manufacturing as well as continuous-type (process-type) manufacturing such as steel, chemical and building construction industries. In addition, advanced manufacturing industry of the future will be expanded to materials manufacturing, i.e. digital design and production of new materials as well as biological production, i.e. digital design and production of biological entities, etc.

2.3 Innovation in industry model

The industry model for the manufacturing industry will undergo enormous changes as a result of digital technology which is supported by the internet, internet of things, cloud computing and large data, etc.

Service industry of product nature will also see full-scale rapid development. Large and medium corporations are moving towards a model featuring "product + service". They are transforming from being product manufacturers to systems integrators and service providers.

Progress in product technology, manufacturing technology and management technology brought about by "digitalization and intelligentization of manufacturing industry" will empower them with the ability for rapidly responding to market demands. In particular they will be able to achieve a synergistic and new production model that is characterized by the ability to adapt to a rich and diverse customer base in the global market, achieve remote customization, off-location design and the local product. All these will bring about fundamental changes in the product manufacturing model, product organization model and corporation's commercial model in many different ways.

In fact, the third round of industrial revolution proposed by some western economists is more from the point of view of the industry model. They feel that the first industrial revolution took place during the 18th Century with the production of large machines, and the second industrial revolution took place during the 20th Century with the large-scale production of machinery, while during the third industrial revolution a new production model featuring multiple types of products, small-batch production and customization will be formed.

One point that cannot be stressed enough is this: Regardless of the angle from which one considers, "digitalization and intelligentization of manufacturing industry" is at the core of the new industrial revolution.

3 Promoting digitalization and intelligentization of manufacturing industry through engineering and commercialization

The key to innovation-driven development is the promotion of tight connection between sci-tech and the economy. Thus the most important aspect for digitalization and intelligentization of China's manufacturing industry is to promote engineering and commercialization.

Innovation means creation of new things. This concept is now given a deep and highly important meaning. There are three terms in the English language: discovery, invention and innovation. They are connected but with fundamental differences. To put it simply, "discovery" refers to scientific discovery, while "invention" refers to scientific and technological invention, and "innovation" refers to technological innovation. Both scientific discovery and technological inventions need to be engineered and commercialized. Innovation can be as such only if something is truly converted into productivity. Engineering and commercialization link scientific and technological innovation and industrial development together closely. This is an important aspect of innovation, a decisive factor for enabling structural adjustments in industry and fully enhancing industry competitiveness. It holds the key to innovation-driven development.

During the digitalization and intelligentalization of the manufacturing industry, we would need to firmly establish the idea of innovation spurring development. We would need to further liberate our ideas and undertake innovation in relation to organization, integration and synergy. We should ensure liberation and development of scientific and technological production capacity, in particular pushing for engineering and commercialization of scientific and technological results. To do so we would firstly need to leverage on China's superiority in organization. Overall plans should be made by the government and efforts should be made in measured steps to secure key breakthroughs even while promotion is carried out across-the-board. We should mobilize the populace and use our best men and women to carry out innovation in an organized manner. The second point is quickening the pace for in-depth integration of informationalization and industrialization. Information technology with digitalization and intelligentization at its core should be applied to transform and upgrade traditional manufacturing industry to achieve integration innovation. Finally, an innovative system should be established, taking enterprises as the main body, staging market-oriented and attaching great importance to the integration of enterprises, institutions of higher learning and research institutes.

Our comrades in China's manufacturing industry have a common aim, that is, by 2020, China's mechanical products should be under numerical control in order for the industry to be upgraded to "numerical control generation". NC technology should be applied throughout China's manufacturing industry, with certain level of intelligentization achieved in a number of fields. By 2030, China's mechanical products should be upgraded to "AI generation". The intelligent production model should be fully implemented in major areas of China's manufacturing industry such that China would be among the top in the world. In short, they should make strategic, key and fundamental contribution to China's modernization.