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Upgrading Pathways of Intelligent Manufacturing in China: Transitioning across Technological Paradigms

Yuan Zhou [a], Jiyuan Zang [a,b,*], Zhongzhen Miao [a,*], Tim Minshall [c]

[a] School of Public Policy and Management, Tsinghua University, Beijing 100084, China
[b] Center for Strategic Studies, Chinese Academy of Engineering, Beijing 100088, China
[c] Institute for Manufacturing, University of Cambridge, Cambridge CB3 0FS, UK

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ABSTRACT

Intelligent technologies are leading to the next wave of industrial revolution in manufacturing. In developed economies, firms are embracing these advanced technologies following a sequential upgrading strategy—from digital manufacturing to smart manufacturing (digital-networked), and then to new-generation intelligent manufacturing paradigms. However, Chinese firms face a different scenario. On the one hand, they have diverse technological bases that vary from low-end electrified machinery to leading-edge digital-network technologies; thus, they may not follow an identical upgrading pathway. On the other hand, Chinese firms aim to rapidly catch up and transition from technology followers to probable frontrunners; thus, the turbulences in the transitioning phase may trigger a precious opportunity for leapfrogging, if Chinese manufacturers can swiftly acquire domain expertise through the adoption of intelligent manufacturing technologies. This study addresses the following question by conducting multiple case studies: Can Chinese firms upgrade intelligent manufacturing through different pathways than the sequential one followed in developed economies? The data sources include semi-structured interviews and archival data. This study finds that Chinese manufacturing firms have a variety of pathways to transition across the three technological paradigms of intelligent manufacturing in non-consecutive ways. This finding implies that Chinese firms may strategize their own upgrading pathways toward intelligent manufacturing according to their capabilities and industrial specifics; furthermore, this finding can be extended to other catching-up economies. This paper provides a strategic roadmap as an explanatory guide to manufacturing firms, policymakers, and investors.

1. Introduction

Intelligent manufacturing is a general concept that covers a range of specific components, which involve digitalization, networkization, and intelligentization technologies in the manufacturing industry [1–4]. In recent years, the uprising of new-generation information technologies (e.g., artificial intelligence (AI), big data) have brought important opportunities to upgrade manufacturing technologies toward intelligent manufacturing [3,5–13]. It runs through every link in the full value chain of design, production, products, and services, as well as the optimization and integration of corresponding systems [14,15]. This shift will lead to the next wave of industrial revolution in manufacturing, which will significantly upgrade firms' product quality, performance, and service levels while reducing resource consumption [16–20].

Developed countries are actively engaging in the new wave of intelligent manufacturing [21]. For example, the United States has launched the Advanced Manufacturing Partnership [22,23], Germany has developed the strategic initiative Industry 4.0 [24], and the United Kingdom has put forward the UK Industry 2050 strategy [25]. Many other countries have launched similar programme to encourage the embracement of intelligent manufacturing [26–28]. These initiatives sometimes bring a dilemma to manufacturing firms—they face the institutional isomorphic pressure especially when those lead firms have committed to the state-of-the-art intelligent manufacturing and have secured tentative success in pilot projects [29–31]. However, manufacturers are also cautious to embrace intelligent manufacturing technologies

* Corresponding authors.
E-mail addresses: zangjiyuan@126.com (J. Zang), zhongzhenmiao@live.com (Z. Miao).

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that are viewed as highly uncertain and costly [32–35]. In reality, many manufacturing firms employ a sequential upgrading strategy (step-by-step) over decades across three technological paradigms—from digital manufacturing to smart manufacturing, and then to new-generation intelligent manufacturing technologies. This sequential pathway has become routine/practice for many latecomers, and most believe that it is necessary to adopt these technologies in series [36–39].

However, Chinese firms face a much different scenario [40–43]. On the one hand, they have diverse technological bases that vary from low-end electrified machineries to leading-edge digital-network technologies—they may not follow an identical upgrading pathway [44–46]. On the other hand, Chinese firms aim to catch up in a fast pace from technology followers to probable frontrunners; thus, the turbulences in the transitioning phase may trigger a precious opportunity for leapfrogging, if Chinese manufacturers can swiftly acquire domain expertise through the adoption of intelligent manufacturing technologies [47–50]. These concerns create both challenges and opportunities for Chinese manufacturers.

This study, therefore, will address the following question by conducting multiple case studies [51–53]: Can Chinese firms adopt intelligent manufacturing technologies in different pathways compared to the sequential one followed in developed economies [54,55]? The data source includes semi-structured interviews and archival data, all of which are collected for a national consultancy project of Chinese Academy of Engineering named "Research on the strategy of Manufacturing Power towards 2035." Interview transcripts and other documents are analyzed using thematic analysis method [56] to explore the upgrading pathways of intelligent manufacturing in China. This study finds that Chinese manufacturing firms have a variety of pathways to transition across the three technological paradigms of intelligent manufacturing not in series. This finding implies that Chinese firms may strategize their own upgrading pathways toward intelligent manufacturing according to their capabilities and industrial specifics. We argue that firms need to fully consider a variety of determinants that may lead to different pathways, such as their business models, manufacturing bases, technology appropriability regime, organizational routines, and more specifically, on the heterogeneity of the three technological paradigms of intelligent manufacturing: digital manufacturing, smart manufacturing, and new-generation intelligent manufacturing [57–59]. These findings can be extended to other catching-up economies. This paper provides a strategic "roadmap" as an explanatory guide to manufacturing firms, policymakers, and investors concerned about developing economies [60,61].

2. The three technological paradigms of intelligent manufacturing

Intelligent manufacturing contains three technological paradigms including digital manufacturing, smart manufacturing, and new-generation intelligent manufacturing [1]. It is a highly complex system technology that integrates advanced manufacturing and information technologies [62].

2.1. Intelligent manufacturing technologies for advanced manufacturing

Intelligent manufacturing is a generic enabling technology that involves three major components of the complex systems across manufacturing sectors [63]. It leads to new technological paradigms in manufacturing in terms of new technologies, new business models, and new ecosystems [64]. It can be applied in all value chains like product design, production process, logistics, and service to significantly improve product quality and production efficiency [65].

Intelligent manufacturing brings significant impacts on existing manufacturing sectors in three folds. First, digitalization technologies add "brains" to products [66,67]. Second, networkization technologies allow low-cost and wide-ranging connections amongst equipment and products [68]. Third, intelligentization technologies (AI and big data) allow products to have "sensing and learning" capabilities, which consequently lead to fundamental change to product functionality and performance [64,69].

Based on these three core components, the evolution of intelligent manufacturing consists of three technological paradigms, including digital manufacturing, smart manufacturing, and new-generation intelligent manufacturing (Fig. 1) [1,64]. Digital manufacturing involves digitalization technologies such as enterprise resource planning (ERP), office automation (OA), manufacturing execution systems (MES), and supply chain management (SCM), which fall under the German definition of Industry 3.0 [66,70]. Smart manufacturing combines digitalization and networkization technologies, such as e-commerce, the Internet of Things (IoT), and online coloration platforms, which fall under the German definition of Industry 4.0 [71,72]. New-generation intelligent manufacturing integrates digitalization, networkization, and intelligentization technologies, for instance predictive maintenance (PdM), remote maintenance platforms, and cognitive learning capability in products, production, and services [73,74]. This form of manufacturing represents the future landscape of intelligent manufacturing development [75].

2.2. Transitioning across the three paradigms in series or not

All three technological paradigms of intelligent manufacturing have specific characteristics and transitioning barriers that need to be solved for upgrading. To be specific, the digital manufacturing paradigm requires production processes to be upgraded from analog or manual control to digital control using computing, communication, and control (3C) technologies [76,77]. The aim of this upgrading is to increase product quality and production efficiency. The smart manufacturing paradigm focuses on building low-cost equipment-to-equipment connections, equipment-to-system connections, and the Internet of Everything (IoE). Such wide-ranging connections facilitate the development of new business models such as PdM and mass customization. Germany's Industry 4.0 and the Industrial Internet of the United States both refer to this paradigm of manufacturing [59,78,79]. The new-generation intelligent manufacturing paradigm requires the integration of manufacturing and advanced information technologies with significant improvements in cognitive learning, data processing, computing, and IoT technologies. The most fundamental feature of the new-generation intelligent manufacturing paradigm is that cognitive and learning functions are added to the complex system [1,64,80,81].

In fact, digitalization, networkization, and intelligentization manufacturing technologies are involved in all three paradigms of intelligent manufacturing development (Fig. 2). For example, the digital manufacturing paradigm not only involves various digitalization technologies, but also integrated networkization and intelligentization technologies such as bus and expert systems in the early days. The smart manufacturing paradigm is based on low-cost data interchanges introduced by the development of information and communication technologies (ICTs). Such interchanges ease data collection and digitalized human–machine interaction, and form the foundation of early-stage big data analysis and AI technologies. As a newly emerged manufacturing paradigm, new-generation intelligent manufacturing should involve cognitive learning and AI-based decision-making technologies,

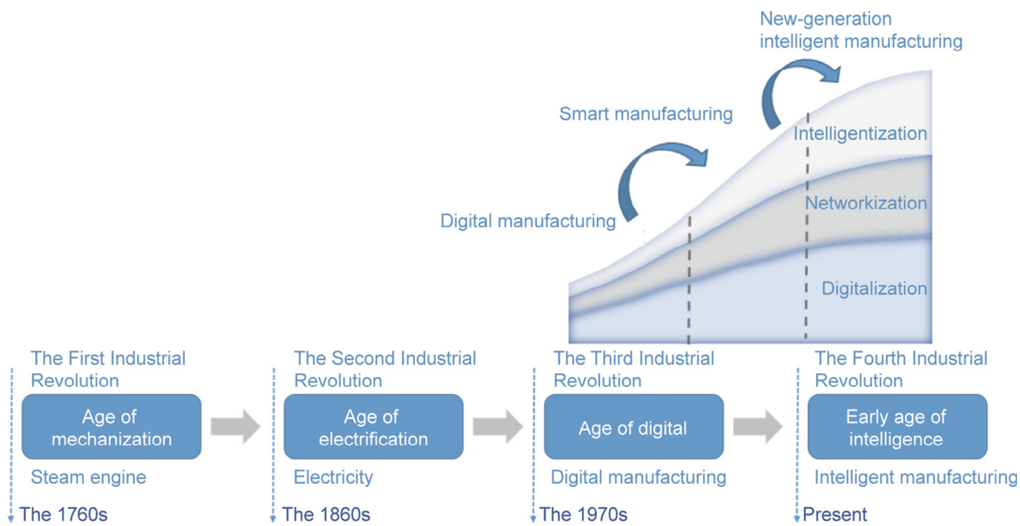

Fig. 1. The four industrial revolutions and the three technological paradigms of intelligent manufacturing.

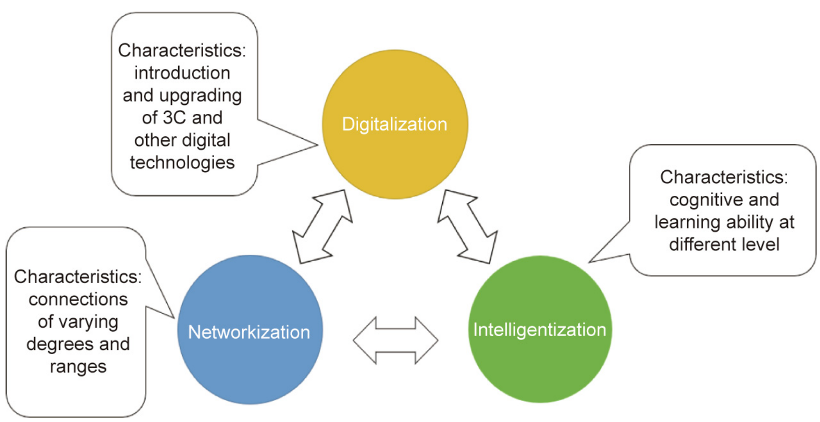

Fig. 2. Three core components of intelligent manufacturing and their respective characteristics.

and will integrate prior digitalization and networkization technologies while significantly improving their efficiency and effectiveness. Such technologies include: the perception, visualization, and transmission of information; digital twins; simulation and modeling; control; and human–machine interactions [82–84].

In this paper, the characteristics of the three technological paradigms of intelligent manufacturing have been summarized for case analysis. These indicators are developed based on a review of the existing literature and experts' discussion; they are listed in Table 1 [1,4,6,38,45,62,64,67,68] together with corresponding codes that are used to describe the level of a variety of intelligent manufacturing technologies in the following case analyses.

2.3. Upgrading pathway of intelligent manufacturing in developed economies

Since the emergence of digital technologies in the 1950s, digitalized equipment such as computers and computer numerical control (CNC) machines have been introduced into the manufacturing sector [57,66]. By the early 21st century, based on continuous development of the digital manufacturing paradigm, the smart manufacturing paradigm emerged following the wide-ranged adoption of ICT technologies [5,9,68]. After development over several decades, the manufacturing sectors in the United States and Germany had already become fully digitalized by the time smart manufacturing technologies were introduced [2,13]. Fig. 3 describes the upgrading pathway of intelligent manufacturing in developed countries, where "D" refers to the digitalization technologies, "N" refers to the networkization technologies, and "I" refers to the intelligentization technologies. Along this evolution pathway, we can identify three major stages that denotes the three technological paradigms: at stage one, digital manufacturing paradigm consists of all three components of intelligent manufacturing, but digitalization technologies play a dominant role; at stage two, smart manufacturing paradigm features both digitalization and networkization technologies that are combined in most cases; at stage three, new-generation intelligent manufacturing paradigm newly emerges, and integrates all three core components of intelligent manufacturing—but this paradigm is still in embryonic state, while upgrading pathways are still muddled to firms even in developed countries (in dashed lines in Fig. 3).

Germany's Industry 4.0 and National Industrial Strategy 2030 [85] both aim to guide firms to adopt smart manufacturing technologies using an approach of "manufacturing + internet," which belongs to the smart manufacturing paradigm. Germany is taking full advantage of its strong capability in digitalized manufacturing and industrial bases by combining network technologies with existing equipment.

The Industrial Internet proposed by the United States uses an approach of "internet + manufacturing," which also falls under the smart manufacturing paradigm. Because the United States has world-leading Internet and ICT sectors, it chooses to upgrade

Table 1
Coding of digital, smart, and new-generation intelligent manufacturing.

Core components of intelligent manufacturing	Codes	Characteristics	Refs.
Digitalization	D0	No digitalization	[1]
	D1	Digitalization in production equipment, design and/or production management (i.e., PLC, DCS, SCADA, ERP, OA, MES, WMS, SCM, CRM, CAD/E/X, and visualization of production processes); not world-leading in these areas	[1,4,67]
	D2	Clear digitalization strategy of firm; digitalized production management; digital twins; integration of production process using digital technologies	[1,4,64]
Networkization	N0	No network-based technologies adopted	[1]
	N1	Network-enabled product, production and/or service; including network technologies used for integration of supply chain and/or value chain, establishment of design and/or production platform, inter-firm collaboration, customization on online orders, Industrial Internet, PdM, etc.	[1,64,68]
	N2	Network technologies widely used in products, production and services; IoT; vertical and horizontal integration of information flow along the supply and value chains; optimization of resource allocation through online platforms; inter-firm collaboration online; online service reaching out to customers to understand personal needs, provide product maintenance, etc.; the focus of firms' business transforms from a production bases to engineering services providers	[1,6,64,68]
Intelligentization	I0	No application of intelligent technologies	[1]
	I1	Introduction of deep learning, reinforcement learning, transfer learning, big data and/or human–machine hybrid intelligence; cognitive and learning capabilities, which allow optimization and logical reasoning, in products, production and/or services; examples include PdM, remote maintenance platforms, etc.	[1,4,45]
	I2	Production system has "cognitive learning" capabilities; comprehensive use of deep learning, reinforcement learning, transfer learning, big data and/or human–machine hybrid intelligence; revolutionary breakthroughs in manufacturing knowledge creation, acquisition, application, and regeneration; significant improvement in innovation and service capabilities; examples include PdM and independent production under complex circumstances	[1,4,38,45,62]

PLC: programmable logic controller; DCS: distributed control system; SCADA: supervisory control and data acquisition; WMS: warehouse management system; CRM: customer relationship management; CAD/E/X: computer-aided design/engineering/all.

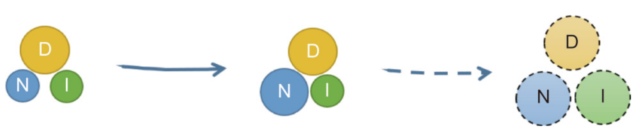

Fig. 3. Upgrading pathways of intelligent manufacturing in developed countries.

its manufacturing sector by developing internet-based production platforms to form new production models.

However, Chinese firms face a much different scenario, as they need to catch up over a much shorter cycle by transitioning across three complex technological paradigms. Thus, their transition effort faces more complicated barriers that require further in-depth enquiry.

3. Case studies: Upgrading pathways of intelligent manufacturing in China

China is a latecomer to industrialization for historical reasons over the last decades. Starting with its reform and opening up in 1978, China entered a new era of rapid development in industrial technologies. Thanks to the wide-ranging adoption of internet technologies, Chinese manufacturing has gradually caught up with the manufacturing sectors of developed countries; in fact, some Chinese firms have succeeded in not only catching up, but also becoming frontrunners.

The upgrading pathways of intelligent manufacturing involves transitioning across three technological paradigms, the earliest of which began in the 1950s and the latest of which has yet to be formally finalized. Chinese manufacturers need to catch up over a much shorter cycle, so they must make their transitions across these paradigms as quickly as possible. Therefore, it is unlikely that Chinese firms will follow the sequential pathway of upgrading intelligent manufacturing that has been used by firms in developed economies—Chinese firms do not have sufficient time within the window of opportunity.

Most manufacturing firms in China remain in the digitalization stage; thus, there are substantial gaps between such firms and their international competitors. In the last two decades, leading firms in the ICT and manufacturing sectors in China have begun to invest heavily in the Industrial Internet and cloud computing in the manufacturing sectors. Follower firms in China are rapidly exploring the opportunities being opened by "internet + manufacturing." They are developing network-enabled products, production, and services in order to improve product quality, production efficiency, market responsiveness, and so forth. With the adoption of "Internet+" technologies, some firms have transformed from being users of traditional production techniques (i.e., manual equipment) to being adopters of network-based manufacturing technologies. During this transformation process, Chinese firms have gone through various pathways, which will be studied in this paper.

3.1. Transitioning across the three technological paradigms in series

During the upgrading of manufacturing capabilities, a group of Chinese firms with a good foundation in the digital manufacturing paradigm was able to successfully transition to the smart manufacturing paradigm, thereby becoming a demonstration project for "internet + manufacturing" in China. SANY Heavy Industry Co., Ltd. (hereafter referred as SANY) is one of these firms.

Case 1: SANY was founded in 1994 and produces concrete equipment, excavators, cranes, and so forth. It is one of the world's leading providers of engineering equipment by far, as well as being the top provider of concrete-pump cars in the world. SANY was the first firm in China's engineering equipment sector to develop and adopt smart manufacturing technologies, which significantly improved the quality of its products. Following the digitalization of its production, SANY actively built a global IoT system and a big data platform to provide services such as PdM and IoT financial services, all of which have contributed to SANY's success.

SANY has made the digitalization of production a top priority in its strategy since the firm was founded. SANY has a firm-level strategy to control its digitalization process, which ensures that a good foundation is built before moving toward the next target. Between 1994 and 2004, SANY digitalized its key designing process and management system, and gradually integrated digitalized management into its daily routines.

With SANY's expansion, independent business management modules no longer met its need for a highly integrated management system. Thus, SANY spent a decade on using network technologies to link all independent modules starting in 2004. During this decade, a first-generation interconnected management system was built to share data and synchronize tasks between the design module and management module. Later on, SANY built a global operational management system to link and optimize the functionality of the subsystems built previously; this allowed it to start a new business model named "the internet of manufacturing." After Internet of Vehicles (IoV) technologies were introduced, SANY's management system extended toward the consumer end, forming a vertically integrated system from the customer end to the production end. The global platform also horizontally integrates the management of domestic and overseas business units, including SANY's marketing, sales, and after-sale services. With this highly integrated global platform, SANY built its market-analyzing system to further improve its responsiveness to the international market. In addition, it built a global collaborative R&D platform using network-enabled virtue reality (VR) and simulation technologies.

In 2015, manufacturing became one of China's critical national strategies, and Chinese firms actively responded to this strategy to conduct intelligent manufacturing upgrading. Since 2018, SANY has begun to explore the applications of AI in its products, production and services, thus taking the first step toward the new-generation intelligent manufacturing paradigm. It has developed several unmanned heavy machineries, including excavators and cranes, which can be remotely controlled with precision. Based on IoV technologies, SANY monitors and provides diagnostics for its products in real time. All data collected are used to provide high-value-adding services such as PdM and IoT finance.

From the timeline of SANY's implementation of intelligent manufacturing technologies (Table 2), it is found that this firm has upgraded across the three technological paradigms in series (Fig. 4).

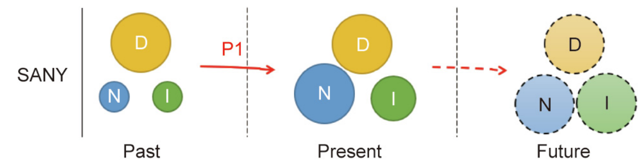

Fig. 4. Case 1: SANY's upgrading pathway (P1) of intelligent manufacturing.

3.2. Transitioning across the three technological paradigms in non-linear ways

In the three technological paradigms, digitalization technologies always lay the ground for networkization and intelligentization technologies. However, some firms realize that these three technologies can be adopted in parallel, while digitalization technologies are not necessarily a prerequisite for the employment of the other two types of technology. This implies that some firms may be able to leapfrog, in specific circumstances, into the smart manufacturing paradigm despite starting with a limited bases of digitalization technologies.

Case 2: Zhejiang CFMOTO Power Co., Ltd. (hereafter referred as CFMOTO) started as a workshop-style plant in 1989; it now produces the world's most reliable and cost-effective motorcycles, all-terrain vehicles, side-by-side utility vehicles, and powersports engines, parts, gears, and accessories. Since 2007, CFMOTO has become a world-leading producer in the specialized vehicles sector, with a market share that has remained the highest in the European market for 12 years. With the rapid expansion of CFMOTO's business, a new business model and a new management system were urgently needed in order to improve operational efficiency and market responsiveness. In response to rapidly changing consumer needs, CFMOTO initiated a transformation of its business model toward mass customization, flexible manufacturing, e-commerce, and so forth.

Like most Chinese manufacturing firms before 2012, CFMOTO had only a few independent digitalized systems such as ERP (D1), OA (D1), and product data management (PDM) (D1). Due to the increasing demand for producing small batch orders with large variety, a short leading time, and higher quality requirements, CFMOTO developed a firm-level strategy to implement intelligent technologies.

Based on its existing production capabilities, CFMOTO chose to start a new business model based on mass-customized special vehicle manufacturing. In order to build the business model, the firm started to restructure, optimize procedures, and upgrade hardware (D1) in 2013. During the digitalization process, CFMOTO focused on adopting the cutting-edge technologies of that time to aid its transformation. Since 2014, CFMOTO has established several network-enabled systems including an IoT system (D1N1), SCM (D1N1), product life-cycle management (PLM) (D1N1), and ERP (D1N1). With these systems, production can be automatically managed and controlled. By 2015, all these systems had been linked together, allowing information to flow freely along the value chain. From 2016 to 2018, the transformation toward the new business model was completed. As one of demonstration projects funded by China's Ministry of Industry and Information Technology, customer orders with CFMOTO could directly reach the

Table 2
Timeline of SANY's adoption of intelligent manufacturing technologies.

Year	Progress in developing intelligent manufacturing technologies	Code
1994–2004	CAD (D1); SAP (D1); accounting system (D1); data center (D1); OA (D1); global video conference system (N1)	D1N1
2004–2014	Three-dimensional design (D1); PDM (D1); PLM (D1); global ERP (D1); ECC (D2N1); CRM (N1); SCM (N1); eHR (N1); accounting analysis system (D2N1); MES (D1); largest digital plant in Asia (D2); "internet + manufacturing" (N2); e-commerce (N1)	D2N1
2015	Horizontal integration of value chains (D2N2); market analysis system (D2N2); vertical connection of production process (D2N2); product design based on VR and simulation (D2N2)	D2N2
2018	Unmanned machineries (I1); remote maintenance platform (I1); financial service based on IoT and big data (N2)	D2N2I1

Source: adapted based on public documents. CAD: computer-aided design; SAP: system applications and products; PDM: product data management; PLM: product lifecycle management; ECC: ERP central component; eHR: e-human resource.

production site, in a process named "customer to manufacturer" (C2M) (D2N2).

From 2018 to the present, CFMOTO has shifted its focus from building smart production plants to online platform development. It has established several online platforms to form its core competitive advantages, including a data-driven designing platform (D2N2), IoV (D2N1), and a big data operation platform (D2N2).

From the timeline of CFMOTO's implementation of intelligent manufacturing technologies (Table 3), it is found that this firm upgraded across the three technological paradigms not in a sequential order (Fig. 5).

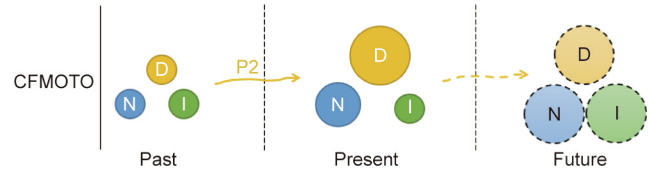

Fig. 5. Case 2: CFMOTO's upgrading pathway (P2) of intelligent manufacturing.

Case 3: Qingdao Kute Smart Co., Ltd. (hereafter referred as Kute) was founded in 1995 as a traditional garment maker. In the last decades, it has built an "Internet+" manufacturing system to provide mass-customized clothing. In addition, it has built digitalized designing and logistic platforms, which form two critical parts of its business model. Kute used internet technologies to develop a communication system linking customers directly with factories. This formed a C2M business model that lowers the product price by eliminating distributors.

During the process of adopting intelligent technologies, Kute took the cost and return of introducing new technologies into consideration, which has been the key to its success. The top managers of Kute predicted that the mass production of clothing would be quickly replaced by customized products made in small batches. Therefore, they chose mass customization as their main business model. First, they upgraded their production plants with automated equipment. In 2004, they then introduced the e-commerce system (N1)—much earlier than their competitors.

In the following decade, Kute went through a series of reforms to introduce new technologies. Between 2005 and 2010, it built a company intranet to link individual information systems such as order management systems (OMS) in different factories. This made Kute ready to move the entire system online to form a new business model of C2M (D1N2).

In order to minimize cost and improve product quality, Kute started to introduce a digital production planning system (D1) from 2010 to 2012. By introducing its first self-developed cutting machines, the work efficiency improved more than threefold. By 2017, Kute's labor force in the logistics department had been reduced by over 80% after smart logistics and automated storage systems were introduced. Interestingly, Kute's sewing processes are still done manually today, as the cost of introducing automated sewing machine outweighs the perceived returns. Compared with computer-controlled sewing machines, workers are more flexible in production. Instead of replacing workers, Kute uses a high salary to maintain a stable workforce. Using IoT technologies, Kute monitors the entire production process against key performance indicators (KPIs) automatically generated by the intelligent production management system.

From the timeline of Kute's implementation of intelligent manufacturing technologies (Table 4), it is found that this firm upgraded across the three technological paradigms in non-linear ways (Fig. 6).

Case 4: Xinjiang Goldwind Science & Technology Co., Ltd. (hereafter referred as GoldWind), founded in 1998, is a world-leading manufacturer of wind turbines, with a total installed capacity of 50 GW, distributed in 24 countries worldwide. GoldWind has been listed as one of the World's 50 Most Innovative Companies for many years. As one of the founding firms in the Chinese wind turbine sector, GoldWind's history resembles the history of China's wind turbine development. GoldWind has now transitioned from a wind turbine producer to an engineering firm that provides wind farm design, wind power equipment manufacturing, construction, maintenance, and financial services.

Digitalization has been the top priority of GoldWind since it was founded, and was considered to be a core competitive advantage of the firm. From 2001 to 2012, GoldWind built many systems to improve the efficiency of the firm. It adopted digitalization and networkization technologies simultaneously. By 2012, GoldWind had built a collaborative R&D platform (D1N1), PDM (D1), ERP, SCM (D1), customer relationship management (CRM), e-human resource (eHR), and e-commerce (D1N1). In addition, it built an information management system to support the decision-making of top managers.

In 2013, GoldWind initiated a microgrid demonstration project for wind–photovoltaic storage (D2N1). Using its digitalized product-designing system as a foundation, GoldWind established its online operational platform (D2N2) between 2016 and 2017 to control smart direct-drive wind turbines and other wind farm managing systems, such as New Freemeso, GoldFarm, SOAM, EFarm, Powernest, and ResMart.

Based on all of its previously built subsystems, GoldWind developed its capability to provide full-package solutions for building and managing wind farms. These consist of: the selection of a location for wind farms, accurate monitoring of wind, wind resource assessment, planning and design of windfarms, construction management, capital management, wind power forecasting, smart diagnostics of equipment, and more. By 2019, GoldWind's products and services had been bought by 12 energy firms, applied in 107 windfarms, and used to manage more than 16 000 wind turbines. As a result of the products and services delivered by GoldWind, the overall operational efficiency of the windfarms increased by 10%–15%, the wind resource utility rate rose by 50%–200%, and the margin of windfarms grew by 1%–3%.

From the timeline of GoldWind's implementation of intelligent manufacturing technologies (Table 5), it is found that this firm upgraded across the three technological paradigms not in consecutive order (Fig. 7).

Table 3
Timeline of CFMOTO's adoption of intelligent manufacturing technologies.

Year	Progress in developing intelligent manufacturing technologies	Code
2008–2010	ERP (D1); OA (D1); PDM (D1)	D1
2013	Digitalized production lines (D1); robotic welding (D1); automated electrophoresis	D1
2014	IoT system (D1N1); logistic system; barcode system; SCM (D1N1); PLM (D1N1); ERP (D1N1); eHR system	D1N1
2015–2018	Highly integrated management system; all subsystems interconnected; mass-customized production	D2N1
2018–2019	(In process) data-driven designing platform (D2N2); C2M (D2N2); intelligent precision production platform (D2N2); IoV (D2N1); big data operation platform (D2N2)	D2N2

Source: adapted based on public documents.

Table 4
Timeline of Kute's adoption of intelligent manufacturing technologies.

Year	Progress in developing intelligent manufacturing technologies	Code
2003–2004	Customized products; e-commerce (N1)	D0N1
2005–2010	ERP; OA; MES; WMS (D1); automated design (D1)	D1N1
2010–2012	Digitalization of equipment (D1); digitalized sewing and cutting (D1); APS; SCM; MES; WMS; IMDS; OMS (D1N2); mass customization based on data collected from these systems	D1N2
2015–2018	Digital production equipment (D1); C2M ecosystem, BPM (N1); smart logistics; automated storage (D1); IoT based on digital factory (N2); monitoring production in real time (D1)	D1N2

Source: adapted based on public documents. APS: advanced planning and scheduling; IMDS: international material data system; OMS: order management system; BPM: business process management.

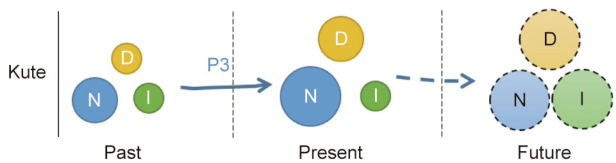

Fig. 6. Case 3: Kute's upgrading pathway (P3) of intelligent manufacturing.

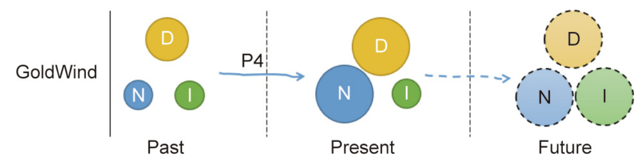

Fig. 7. Case 4: GoldWind's upgrading pathway (P4) of intelligent manufacturing.

3.3. Transitioning across the three technological paradigms with facilitation from third-party integrators

Due to limited financial resources and manufacturing capabilities, small and medium-sized enterprises (SMEs) often cannot transition across the three technological paradigms on their own. Thus, third-party integrators with strong digitalization, networkization, and/or intelligentization technological bases can facilitate SMEs' adoption of intelligent manufacturing technologies with significantly reduced risk and cost.

Case 5: Transformation of a cluster of ball-bearing manufacturers in Xinchang County by Zhejiang TOMAN Precision Machinery Co., Ltd. (hereafter referred as TOMAN). TOMAN, founded in 2006, is a production system integrator in Xinchang, Zhejiang Province, which successfully helped a cluster of ball-bearing manufacturers in Xinchang to upgrade their manufacturing capabilities with intelligent manufacturing technologies in 2016. At that time, there were over 600 ball-bearing manufacturers in Xinchang. Most of these firms did not have digitalized equipment at that time. Due to increasing competition, the profit margin of these firms was just 3%–5%.

Under the pressure of intense market competition, these firms started to transform their business model toward high quality, high efficiency, and low energy consumption. TOMAN took this opportunity to transform from an equipment manufacturer to a production system integrator, with the aim of providing digital and network-enabled production lines (D1N1) to local ball-bearing manufacturers.

In 2006, TOMAN was among the first group of firms to introduce robotic technologies in Zhejiang. Its main product was automated equipment for producing ball bearings, gears, and auto parts. Due to a deep understanding of local SMEs' demands, TOMAN had sold equipment to over 1200 firms.

In 2013, TOMAN started to introduce intelligent manufacturing technologies with the aim of improving product quality and production efficiency, and reducing costs. In 2014, TOMAN started to provide turn-key alike services, including machinery modification. To date, this firm has provided production solutions to over 160 firms, and has modified 12 753 machines using IoT technologies (D1N1). In order to motivate SMEs in Xinchang to adopt intelligent manufacturing technologies, TOMAN established a fund together with the county council. Under the funding scheme, SMEs could have up to 5% of their total equipment modified for free. This small-scale trial project aims to address SMEs' concerns about adopting intelligent manufacturing technologies.

Because intelligent manufacturing technologies are complex system technologies, SMEs generally do not have the capabilities to plan, integrate hardware and software, train employees, and make continuous improvements to their system. Therefore, TOMAN provides customized solutions to SMEs using indigenously developed systems, such as TM-e (a production management system) (D1), TM-SPC (a quality control system) (D1), and TM-ACS (a machinery management system) (D1). These systems are composed of data-collection terminals, cloud platforms, and industrial software applications, which allow SMEs to modify their existing equipment at reduced cost. The average cost of modification is around 0.23 million CNY (approximately estimated from interviews with 55 firms), which can be compensated by the offset from the reduction of labor cost within one year.

In 2017, TOMAN extended its services from the ball-bearing sector to the fixtures and gear manufacturing sectors. Moreover, it built an online industrial platform (N2) in order to rapidly replicate its successful case in Xinchang in other regions.

As a production system integrator, TOMAN's case presents an upgrading pathway of intelligent manufacturing different from

Table 5
Timeline of GoldWind's adoption of intelligent manufacturing technologies.

Year	Progress in developing intelligent manufacturing technologies	Code
2001–2009	OA (D1); GoldWind customer service MIS; ERP (D1); accounting system; production management system; logistic system	D1N0
2009–2012	Collaborative R&D platform (D1N1); PDM (D1); SCM (D1); e-commerce (D1N1); CRM; eHR; MIS (D1)	D1N1
2013–2014	Microgrid demonstration project for wind–photovoltaic storage (D2N1)	D2N1
2015–2019	Smart direct-drive wind turbines (D2N2); new systems including New Freemeso, GoldFarm, SOAM, EFarm, Powernest, and ResMart; built full-package solution for a digitalized wind farm; provides services such as centralized control systems, wind power assessment, equipment maintenance, equipment modification, etc.	D2N2

Source: adapted based on public documents. MIS: management information system.

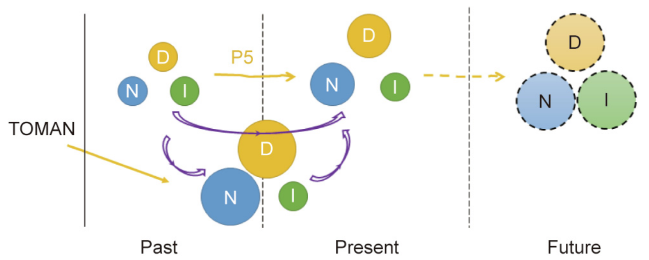

Fig. 8. Case 5: SMEs' upgrading pathway of intelligent manufacturing facilitated by TOMAN.

other four cases studied previously—a pathway that integrators facilitate SMEs in transition across the three technological paradigms. Fig. 8 describes the upgrading pathway of ball-bearing SMEs in Xinchang, where TOMAN is denoted by three circles beneath the upgrading path P5.

4. Cross-case analysis

Upon a comparison of the five cases (Fig. 9), it is found that firms have different pathways when transitioning across the three technological paradigms of intelligent manufacturing technologies. When SANY started to introduce networkization technologies, it already had a good foundation in digitalization technologies. Thus, it transitioned from the digital manufacturing paradigm to the smart manufacturing paradigm directly. In this case, SANY developed the three technological paradigms of intelligent manufacturing in series.

However, CFMOTO, Kute, GoldWind, and TOMAN did not have the same advantage in terms of digitalization technologies. Therefore, these firms developed digitalization and networkization technologies in parallel, using network technologies to drive the digitalization of their business.

CFMOTO started by employing digitalization technologies first, and then introducing networkization technologies once the production processes were fully digitalized. At present, this firm has arrived at the early stage of the smart manufacturing paradigm.

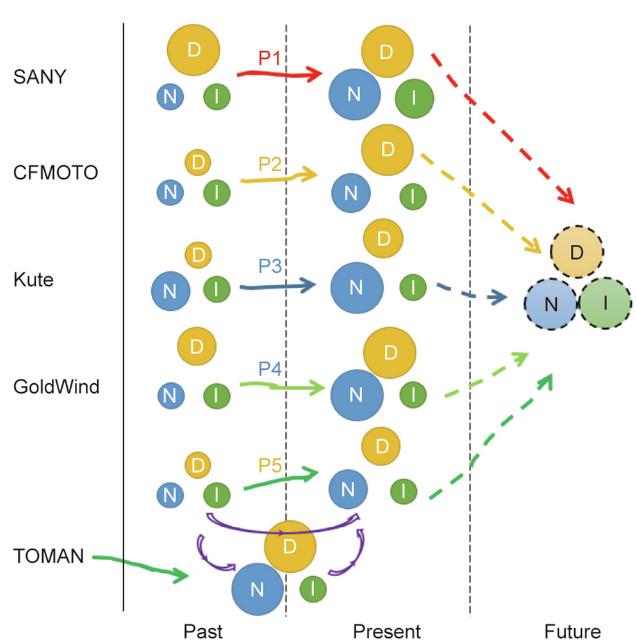

Fig. 9. Upgrading pathways of intelligent manufacturing in all five cases.

Kute started by adopting networkization technologies, and then gradually digitalized its production processes. Although Kute has transitioned to the smart manufacturing paradigm, due to a lack of digitalization technologies being employed, this firm may find upgrading toward the new-generation intelligent manufacturing paradigm challenging in the near future.

GoldWind started by introducing networkization technologies because it had some technological bases of digitalization from the past. With the employment of networkization technologies, the digitalization technology base grew simultaneously, allowing GoldWind to transition from the digital manufacturing paradigm to the smart manufacturing paradigm, where it remains at present.

The case of TOMAN is quite different from the other four cases. The role of TOMAN is to facilitate firms—mostly SMEs with limited resources and capability—in their adoption of intelligent manufacturing technologies. The ways in which SMEs adopt intelligent manufacturing technologies are largely up to their strategy and sectoral specifics. Thus, firms can transition across the three technological paradigms of intelligent manufacturing either in consecutive order or not.

To sum up, the five cases presented here depict five quite different upgrading pathways of intelligent manufacturing in China's manufacturing sectors. The ways in which firms adopt intelligent manufacturing technologies are largely up to their strategy and sectoral specifics. Based on the findings from these five cases, it is reasonable to propose that the upgrading pathway of intelligent manufacturing technologies in China's manufacturing sectors does not have to be in series across the three technological paradigms.

5. Discussion and conclusions

This paper compares five cases that are representative of the intelligent manufacturing upgrading of Chinese firms. Based on these case studies, this paper has summarized the upgrading pathways of every critical case, and has generalized the patterns of upgrading pathways through cross-case comparisons. We argue that in China, manufacturing firms have diverse technological competences, ranging from traditional electrified machinery to network-based manufacturing technologies. In addition, the development of new-generation intelligent manufacturing has just been initiated, which brings further complications to Chinese manufacturers in strategizing their upgrading pathways. This paper has the following key findings.

First, this study finds that Chinese manufacturing firms have employed different upgrading strategies to transition across the three technological paradigms of intelligent manufacturing technologies in a much shorter time than their counterparts in developed economies. The Chinese firms have adopted a variety of upgrading pathways that mostly innovate across the three paradigms not in series. For example, although our five cases had different resource bases and technological competences at the beginning, all of them successfully implemented—through different pathways—digital and network-based manufacturing technologies at the level of D2N2 that help to elevate product quality, production efficiency, and cost management. In addition, few of the firms followed exactly the same linear pathway (i.e., digital → smart → new-generation intelligent manufacturing paradigms) as is typically followed by firms in developed countries. We argue that it is impossible for most Chinese manufacturers, as latecomers, to adopt the in-series upgrading pathway; in fact, by doing so, Chinese firms would lose the leapfrogging opportunity that the wave of intelligent technologies has brought to them. Therefore, we argue that Chinese manufacturers do not have a standardized upgrading pathway that fits every firm; rather, they may have diverse pathways that can help them to better catch up in shorter cycles.

Second, this paper finds that Chinese manufacturers need to strategize their upgrading pathways according to their business models, resource bases, strategic positions, and industrial characteristics. For example, all of the five studied cases designed and implemented their strategy of intelligent manufacturing upgrading successfully, by considering the strategic fit between the specifics of intelligent manufacturing technologies and the firms' own expertise. In addition, we argue that firms need to find a strategic niche to "punch a hole" first, and then follow through; for example, Kute utilizes C2M as its customized design model, and CFMOTO develops modular digital manufacturing in design/logistics and management for integration. Every individual firm has its own strategic niche to break through. Furthermore, we argue that Chinese manufacturers must formulate strategic plans, find strategic niches, and implement plans step by step while considering the firm's specifics. More importantly, firms with better technological competences should fully utilize the leapfrogging opportunities of intelligent technologies. Such firms should invest in and embrace new-generation intelligent technologies such as big data and AI as early as possible so that they may expedite the implementation process throughout the upgrading pathways of intelligent manufacturing technologies.

Third, this papers finds that digitalization technologies lay the groundwork for the upgrading of intelligent manufacturing. Chinese firms should recognize the importance of digitalization technologies, even though such technologies are sometimes not recognized as state-of-the-art. In all five cases—albeit in different stages—the studied firms built specific digitalization technological bases throughout the entire upgrading process, and integrated digitalization technologies with networkization and intelligentization technologies. Otherwise, firms would encounter critical technological barriers thwarting them from stepping into the next upgrading stage. In this sense, Chinese firms may not need to build digitalization technological bases in the first stage, but they need to adopt them along the upgrading process before heading into the ultimate upgrading of intelligent manufacturing that integrates all three technological paradigms.

This paper contributes to the literature on innovation catch-up and manufacturing upgrading in two folds. First, this study extends the catch-up pathway theory to the domain of intelligent manufacturing upgrading—which involves complex system technologies (including the three technological paradigms) and large-scale technological adoptions—and conducts five critical catch-up case studies to generalize the manufacturing upgrading pathways for Chinese manufacturing firms. We argue that Chinese manufacturing firms may not follow a traditional upgrading pathway that is sequential, but may take more diverse pathways that transition across the digital, smart, and new-generation intelligent manufacturing paradigms in non-linear ways and integrate them according to the specifics of the firms. Second, we argue that it is necessary to formulate intelligent manufacturing standards, especially when the upgrading pathways are not standardized. Intelligent manufacturing is a complex system technology concept that consists of three technological paradigms, and firms may be confused when strategizing their pathways for upgrading if there are no collectively agreed-upon standards for manufacturing technologies. For example, our cases of SANY, GoldWind, and Kute took detours when deploying new manufacturing technologies such as ERP and PLM that required more resources and a longer time, especially in the early stages, when the firms had little experience. In this way, the lack of intelligent manufacturing standards made these firms suffer from having to pilot the upgrading programmes. Given the current variety of intelligent manufacturing technologies that are diffusing among a huge number of Chinese manufacturing firms, a lack of manufacturing standards will jeopardize the efforts of these firms and create immense technological barriers for SMEs with limited resources and technological capabilities. This is an issue that requires further attention.

This paper also contributes to policymaking in intelligent manufacturing upgrading. Policymakers are used to designing and implementing industrial policies in a top-down manner; however, we argue that a bottom-up approach is more desirable for intelligent manufacturing upgrading programmes, because top-down policies usually ignore the heterogeneity of the upgrading pathways of Chinese firms. Thus, policymakers should give firms more flexibility in strategizing their own upgrading pathways by considering their own technological competences, resource bases, and industrial specifics, when providing aid for coping with general issues related to public goods and externalities (e.g., generic technologies, technology standards, university–industry collaborations, etc.).

Amid the wave of intelligent manufacturing technologies worldwide, the strategy of upgrading manufacturing technologies in parallel rather than in series (i.e., digitalization → networkization → intelligentization) can be extended to other developing economies. Traditional studies discuss intelligent manufacturing upgrading within the context of developed economies, whose firms spent several decades to upgrade their manufacturing technologies; most of such firms adopted the sequential pathway toward the new-generation intelligent manufacturing paradigm. However, both developing and developed countries are now facing the impacts of intelligent technologies simultaneously, which creates a window of opportunity for developing economies to catch up quickly and even leapfrog over developed economies. Further studies are needed to examine the upgrading of intelligent manufacturing technologies in developing economies, where diverse innovation pathways might be created that will bring even more significant impacts to global manufacturing development as a whole.

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Compliance with ethics guidelines

Yuan Zhou, Jiyuan Zang, Zhongzhen Miao, Tim Minshall declare that they have no conflict of interest or financial conflicts to disclose.

References

[1] Zhou J, Li P, Zhou Y, Wang B, Zang J, Meng L. Toward new-generation intelligent manufacturing. Engineering 2018;4(1):11–20.
[2] Chen Y. Integrated and intelligent manufacturing: perspectives and enablers. Engineering 2017;3(5):588–95.
[3] Kusiak A. Smart manufacturing must embrace big data. Nature 2017;544 (7648):23–5.
[4] National Manufacturing Strategy Advisory Committee, Center for Strategic Studies of CAE. Intelligent manufacturing. Beijing: Publishing House of Electronics Industry; 2014. Chinese.

[5] Tao F, Cheng J, Qi Q, Zhang M, Zhang H, Sui F. Digital twin-driven product design, manufacturing and service with big data. Int J Adv Manuf Technol 2018;94(9–12):3563–76.
[6] Tao F, Qi Q, Liu A, Kusiak A. Data-driven smart manufacturing. J Manuf Syst 2018;48:157–69.
[7] Zhuang YT, Wu F, Chen C, Pan YH. Challenges and opportunities: from big data to knowledge in AI 2.0. Front Inf Technol Electron Eng 2017;18(1):3–14.
[8] Wu J. Age of intelligence: big data and AI redefine the future. Beijing: China CITIC Press; 2016. Chinese.
[9] Kuo YH, Kusiak A. From data to big data in production research: the past and future trends. Int J Prod Res 2018. In Press.
[10] Lee J, Ardakani HD, Yang S, Bagheri B. Industrial big data analytics and cyber-physical systems for future maintenance and service innovation. Procedia CIRP 2015;38:3–7.
[11] Pan Y. Heading toward artificial intelligence 2.0. Engineering 2016;2(4):409–13.
[12] Li BH, Chai XD, Zhang L, Li T, Qing D, Lin T, et al. Preliminary study of modeling and simulation technology oriented to neo-type artificial intelligent systems. J Syst Simul 2018;30(2):349–62. Chinese.
[13] Li BH, Hou BC, Yu WT, Lu XB, Yang CW. Applications of artificial intelligence in intelligent manufacturing: a review. Front Inf Technol Electron Eng 2017;18(1):86–96.
[14] Xiong Y, Wu B, Ding H. The theory and modeling for next generation manufacturing system. China Mech Eng 2000;11(1):49–52. Chinese.
[15] Kusiak A. Fundamentals of smart manufacturing: a multi-thread perspective. Annu Rev Contr 2019;47:214–20.
[16] Bonvillian WB. Technology advanced manufacturing policies and paradigms for innovation. Science 2013;342(6163):1173–5.
[17] Hu SJ. Evolving paradigms of manufacturing: from mass production to mass customization and personalization. Procedia CIRP 2013;7:3–8.
[18] Koren Y. The global manufacturing revolution: product–process–business integration and reconfigurable systems. Hoboken: John Willey & Sons; 2010.
[19] LU Y. Toward green manufacturing and intelligent manufacturing—development road of China manufacturing. China Mech Eng 2010;21:379–86,399. Chinese.
[20] Roper S, Du J, Love JH. Modelling the innovation value chain. Res Policy 2008;37(6–7):961–77.
[21] Esmaeilian B, Behdad S, Wang B. The evolution and future of manufacturing: a review. J Manuf Syst 2016;39:79–100.
[22] Evans PC, Annunziata M. Industrial internet: pushing the boundaries of minds and machines. Boston: General Electric; 2012.
[23] Executive Office of the President, National Science and Technology Council Committee on Technology, National Science and Technology Council. A national strategic plan for advanced manufacturing. Project Report. Executive Office of the President; 2012 Feb.
[24] Kagermann H, Helbig J, Hellinger A, Wahlster W. Recommendations for implementing the strategic initiative Industrie 4.0. Report. Frankfurt: Federal Ministry of Education and Research; 2013.
[25] Eagle P. The future of manufacturing: a new era of opportunity and challenge for the UK. London: The Government Office for Science; 2013.
[26] APO News. Industry Innovation 3.0 [Internet]. Tokyo: Asian Productivity Organization; c2014 [cited 2019 Apr 12]. Available from: https://www.apo-tokyo.org/publications/wp-content/uploads/sites/5/2014_Jul-Aug_p8.pdf.
[27] Gov F. The new face of industry in France. 2017; Available from: https://www.economie.gouv.fr/files/nouvelle_france_industrielle_english.pdf.
[28] Taki H. Towards technological innovation of Society 5.0. J Inst Electr Eng Jpn 2017;137(5):275.
[29] Kong D, Feng Q, Zhou Y, Xue L. Local implementation for green-manufacturing technology diffusion policy in China: from the user firms' perspectives. J Clean Prod 2016;129:113–24.
[30] Kong D, Zhou Y, Liu Y, Xue L. Using the data mining method to assess the innovation gap: a case of industrial robotics in a catching-up country. Technol Forecast Soc Change 2017;119:80–97.
[31] Zhou Y, Dong F, Kong D, Liu Y. Unfolding the convergence process of scientific knowledge for the early identification of emerging technologies. Technol Forecast Soc Change 2019;144:205–20.
[32] Yoshikawa H. Manufacturing and the 21st century—intelligent manufacturing systems and the renaissance of the manufacturing industry. Technol Forecast Soc Change 1995;49(2):195–213.
[33] Li X, Zhou Y, Xue L, Huang L. Roadmapping for industrial emergence and innovation gaps to catch-up: a patent-based analysis of OLED industry in China. Int J Technol Manag 2016;72(1–3):105–43.
[34] Sterman JD. System dynamics modeling: tools for learning in a complex world. IEEE Eng Manage Rev 2001;43(4):8–25.
[35] Nordensvard J, Zhou Y, Zhang X. Innovation core, innovation semi-periphery and technology transfer: The case of wind energy patents. Energy Policy 2018;120:213–27.
[36] Wang Y, Urban F, Zhou Y, Chen L. Comparing the technology trajectories of solar PV and solar water heaters in China: using a patent lens. Sustainability 2018;10(11):4166.
[37] Yang S, Ding H. Research on intelligent manufacturing technology and intelligent manufacturing systems. China Mech Eng 1992;3(2):15–8. Chinese.
[38] Wang B. The future of manufacturing: a new perspective. Engineering 2018;4(5):722–8.
[39] Lin X, Zhou Y, Xue L, Huang L. Integrating bibliometrics and roadmapping methods: a case of dye-sensitized solar cell technology-based industry in China. Technol Forecast Soc Change 2015;97:205–22.
[40] Xu XW, Newman ST. Making CNC machine tools more open, interoperable and intelligent—a review of the technologies. Comput Ind 2006;57(2):141–52.
[41] Xu G, Wu Y, Minshall T, Zhou Y. Exploring innovation ecosystems across science, technology, and business: a case of 3D printing in China. Technol Forecast Soc Change 2017;136:208–21.
[42] Liu P, Zhou Y, Zhou DK, Xue L. Energy performance contract models for the diffusion of green-manufacturing technologies in China: a stakeholder analysis from SMEs' perspective. Energy Policy 2017;106:59–67.
[43] Chen LY, Zhou Y, Zhou D, Xue L. Clustering enterprises into eco-industrial parks: can interfirm alliances help small and medium-sized enterprises? J Clean Prod 2017;168:1070–9.
[44] Zhou Y, Xu G, Minshall T, Liu P. How do public demonstration projects promote green-manufacturing technologies? A case study from China. Sustain Dev 2015;23(4):217–31.
[45] Tan J, Liu D, Liu Z, Cheng J. Research on key technical approaches for the transition from digital manufacturing to intelligent manufacturing. Eng Sci 2017;19(3):39–44. Chinese.
[46] Chen L, Xu J, Zhou Y. Regulating the environmental behavior of manufacturing SMEs: interfirm alliance as a facilitator. J Clean Prod 2017;165:393–404.
[47] Yao XF, Liu M, Zhang J, Tao T, Lan H, Ge D, et al. History and future of intelligent manufacturing from the perspective of AI. Comput Integr Manuf Syst 2019;25(1):19–34.
[48] Li BH, Zhang L, Wang S, Tao F, Cao J, Jiang X, et al. Cloud manufacturing: a new service-oriented networked manufacturing model. Comput Integr Manuf Syst 2010;16(01). 1–7,16.
[49] Tao F, Zhang M, Nee AYC. Digital twin driven smart manufacturing. New York: Academic Press; 2019. p. 282.
[50] Jeschke S, Brecher C, Meisen T, Özdemir D, Eschert T. Industrial internet of things and cyber manufacturing systems. In: Jeschke S, Brecher C, Song H, Rawat DB, editors. Industrial internet of things. Cham: Springer; 2017. p. 3–19.
[51] Yin RK. Case study research: design and methods. Newbury Park: SAGE Publication; 1989.
[52] Yin RK. Case study research: design and methods. 3rd ed. Thousand oaks: SAGE Publications; 2009.
[53] Eisenhardt KM. Building theories from case study research. Acad Manage Rev 1989;14(4):532–50.
[54] Liang S, Rajora M, Liu X, Yue C, Zou P, Wang L. Intelligent manufacturing systems: a review. Int J Mech Eng Rob Res 2018;7(3):324–30.
[55] Zhou Y, Lin H, Liu Y, Ding W. A novel method to identify emerging technologies using a semi-supervised topic clustering model: a case of 3D printing industry. Scientometrics 2019;120(1):167–85.
[56] Miles MB, Huberman AM, Saldana J. Qualitative data analysis: a method sourcebook. 3rd ed. New York: Sage Publications; 2014.
[57] Yan J. Digitalization and networked manufacturing. Ind Eng Manage 2000;1:8–11. Chinese.
[58] Yang S, Wu B, Hu C, Cheng T. Networked manufacturing and enterprise integration. China Mech Eng 2000;1:45–8. Chinese.
[59] Uhlemann THJ, Lehmann C, Steinhilper R. The digital twin: realizing the cyber–physical production system for Industry 4.0. Procedia Cirp 2017;61:335–40.
[60] Yuan Z, Li X, Lema R, Urban F. Comparing the knowledge bases of wind turbine firms in Asia and Europe: patent trajectories, networks, and globalisation. Sci Public Policy 2016;43(2):1–16.
[61] Zhou Y, Pan M, Urban F. Comparing the international knowledge flow of China's wind and solar photovoltaic (PV) industries: patent analysis and implications for sustainable development. Sustainability 2018;10(6):1883.
[62] Zhong RY, Xu X, Klotz E, Newman ST. Intelligent manufacturing in the context of Industry 4.0: a review. Engineering 2017;3(5):616–30.
[63] Li H, Si H. Control for intelligent manufacturing: a multiscale challenge. Engineering 2017;3(5):608–15.
[64] Zang J, Wang B, Liu M, Zhou Y. Brief analysis on three basic paradigms of intelligent manufacturing. Strategic Study CAE 2018;20(4):13–8. Chinese.
[65] Hu H, Zhao M, Ning Z. Three-body intelligence revolution. Beijing: China Machine Press; 2016.
[66] Chryssolouris G, Mavrikios D, Papakostas N, Mourtzis D, Michalos G, Georgoulias K. Digital manufacturing: history, perspectives, and outlook. Proc Inst Mech Eng 2009;223(5):451–62.
[67] Chen D, Heyer S, Ibbotson S, Salonitis K, Steingrímsson JG, Thiede S. Direct digital manufacturing: definition, evolution, and sustainability implications. J Clean Prod 2015;107:615–25.
[68] Mittal S, Khan MA, Wuest T. Smart manufacturing: characteristics and technologies. In: Harik R, Rivest L, Bernard A, Eynard B, Bouras A, editors. Product lifecycle management for digital transformation of industries. Cham: Springer; 2018.
[69] Li J, Qiu B, Liu Z, Wei M. CPS: new-generation AI. Shanghai: Shanghai Jiao Tong University Press; 2017. Chinese.
[70] Zhang H, Zhang H, Ding M. How public demonstration projects affect the emergence of new industries: an empirical study of electric vehicles in China. Innovation 2015;17(2):159–81.
[71] China Electronics Standardization Institute. Cyber–physical systems white paper (2017). Report. Beijing: China Electronics Standardization Institute; 2017. Chinese.

[72] China Electronics Standardization Institute. White paper on standardization of industrial internet platforms (2018). Report. Beijing: China Electronics Standardization Institute; 2018. Chinese.
[73] Hedberg Jr TD, Hartman NW, Rosche P, Fischer K. Identified research directions for using manufacturing knowledge earlier in the product lifecycle. Int J Prod Res 2017;55(3):819–27.
[74] Rosen R, Von Wichert G, Lo G, Bettenhausen KD. About the importance of autonomy and digital twins for the future of manufacturing. IFAC Papers Online 2015;48(3):567–72.
[75] Dong X, Mcintyre SH. The second machine age: work, progress, and prosperity in a time of brilliant technologies. Psychiatry 2015;14(11):380–3.
[76] Xun X. Machine Tool 4.0 for the new era of manufacturing. Int J Adv Manuf Technol 2017;92(5–8):1893–900.
[77] Zhang L, Xue L, Zhou Y. How do low-carbon policies promote green diffusion among alliance-based firms in China? An evolutionary-game model of complex networks. J Clean Prod 2019;210:518–29.
[78] Vogel-Heuser B, Wildermann S, Teich J. Towards the co-evolution of industrial products and its production systems by combining models from development and hardware/software deployment in cyber-physical systems. Prod Eng 2017;11(6):687–94.
[79] Pan M, Zhou Y, Zhou DK. Comparing the innovation strategies of Chinese and European wind turbine firms through a patent lens. Environ Innov Soc Transit 2017;30:6–18.
[80] Busnaina AA, Mead J, Isaacs J, Somu S. Nanomanufacturing and sustainability: opportunities and challenges. In: Diallo MS, Fromer NA, Jhon MS, editors. Nanotechnology for sustainable development. Cham: Springer; 2013. p. 331–6.
[81] Wang B, Liu Y, Zhou Y, Wen Z. Emerging nanogenerator technology in China: a review and forecast using integrating bibliometrics, patent analysis and technology roadmapping methods. Nano Energy 2018;46:322–30.
[82] Liu Y, Zhou Y, Liu X, Dong F, Wang C, Wang Z. Wasserstein GAN-based small-sample augmentation for new-generation artificial intelligence: a case study of cancer-staging data in biology. Engineering 2019;5(1):156–63.
[83] Fonseca F, Marcinkowski M, Davis C. Cyber–human systems of thought and understanding. J Assoc Inf Sci Technol 2019;70(4):402–11.
[84] Zhou Y, Pan M, Zhou DK, Xue L. Stakeholder risk and trust perceptions in the diffusion of green manufacturing technologies: evidence from China. J Environ Dev 2018;27(1):46–73.
[85] Federal Ministry for Economic Affairs and Energy. National Industrial Strategy 2030: strategic guidelines for a German and European industrial policy. Industrial Policy. Berlin: Federal Ministry for Economic Affairs and Energy; 2019.