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The Digitization of Design and Manufacturing: A State-of-the-Art Report on the Transition from Strategic Vision to Implementation in Industry

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Abstract

Almost a decade ago, the research community embarked on a journey to realize the old vision of Industry 4.0. Part of this vision was to digitize design and manufacturing systems and processes, aimed at advancing their vertical and horizontal integration into decentralized ecosystems across the entire product development value chain. This process was to include the provision of new data-driven operation and business models, advances in cybersecurity, and the development of a bespoke Industry 4.0 workforce. In this paper, the authors review the state-of-the-art in regard to the progress made to date, from initial vision towards implementation in industry. They identify critical research challenges and gaps that need to be addressed to further advance this transition. The paper closes with a strategic perspective on how the authors anticipate Industry 4.0 to evolve over the next 5 years.

Keywords: Smart manufacturing; end-to-end value chain; platformization

1. Introduction

About ten years ago emerged a need for disruptive change in the manufacturing sector. It was driven by the need to meet customers' individual preferences in a more timely and cost-effective manner and triggered the initial vision of Industry 4.0 (I4), first in Germany in 2011 [1]. At the same time, similar initiatives developed in other countries around the world. Amongst others, the US saw the advent of a Smart Manufacturing initiative along with the foundation of the Digital Manufacturing & Design Innovation Institute (DMDII), China embarked on its Made in China 2025 mission, in the Netherlands the term Smart Industry was coined, and the Japanese launched their Robot Revolution Initiative 5.0 [2, 3].

I4 is a broad vision supported by frameworks and reference architectures for its implementation, mainly characterized by the integration of physical industrial assets with digital technologies to form so-called cyber-physical systems for production engineering [3]. Initially, the main goals for I4 were to utilize digitization to increase automation across the manufacturing domain and to improve or optimize its production processes. Soon after though more mature goals were identified. These included the exploration of new value streams based on process digitisation and related data, and a need for bespoke I4-relevant business models [3]. All these were meant to achieve enhanced productivity levels, the utilization of real-time data for an agile real-time supply chain in a real-time economy, higher business continuity through advanced maintenance and monitoring possibilities, better quality products through real-time monitoring, IoT-enabled quality improvement, the introduction of cobots, better working conditions and sustainability, increased product personalization and customization (lot size one), improved overall agility, and the development of new innovation capabilities and revenue models [3].

The overarching aim of the paper is to review how much of this initial bold I4 vision has already been realized and how the field can be anticipated to develop in future. In Section 2, the main building blocks of I4 and their adoption are reviewed. In Section 3, immediate challenges and arising opportunities of I4 are presented. Section 4 provides a discussion on how the field

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can be anticipated to develop in the near future. Lastly, the closure of the paper is presented in Section 5.

2. State-of-the-Art (Part 1)

Industry 4.0 stands for a bold vision, built upon a strategic roadmap and being realized through a number of national initiatives. The realization of this process is visualized in four waves based on the extensive literature review, see Fig. 1.

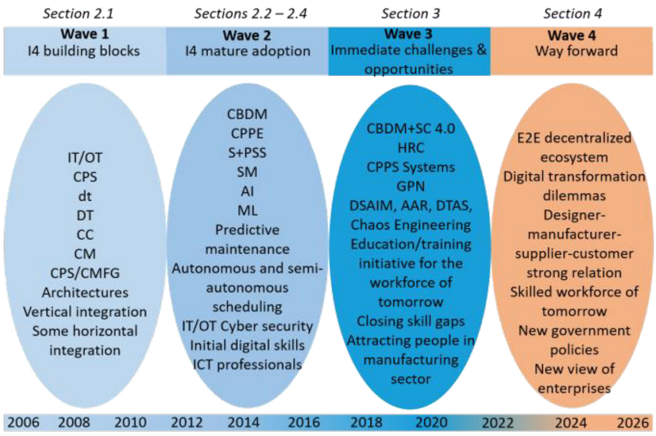

Figure 1: I4 Roadmap

2.1. Building blocks of I4

In this first phase an early adoption of the main I4 principles and technological building blocks can be seen. They include Cyber-Physical Systems (CPS), the (Industrial) Internet of Things (IIoT), Digital Twins (DT), Digital Threads (DT), and Cloud Computing (CC)) [4]. The main efforts observed were focused on defining architecture models for the implementation of CPS for production engineering at a high level of abstraction, with Cloud Manufacturing (CM) being a specific and prominent representative of such systems. Subsequently, research and development efforts shifted towards actual system implementations including both vertically and horizontally integrated manufacturing system entities [5]. Vertical integration predominantly facilitates information flow between the enterprise and its resource planning entities, manufacturing services, as well as the planning and control entities within and across a manufacturing facility [5]. Horizontal integration beyond the boundaries of an enterprise is concerned with and represented through several digital twins mirroring the supply chain and manufacturing processes, data flow across IT systems in product development, logistics, distribution of produced goods, and ultimately the customer [6]. While reasonable progress in terms of vertical integration was achieved in Wave 1, horizontal integration remained a challenge for years to come.

In the early adoption of I4 there were no indication of cyber security and digital workforce in I4.

2.2. Mature adoption of I4

During the second wave of the 4th Industrial Revolution, in progress it can be said, companies expanded their efforts to realize vertical integration of cyber-physical manufacturing entities by improving automated materials flow across the enterprise, autonomous resource allocation, manufacturing process scheduling, and big date-driven predictive maintenance activities [7]. Along with this, manufacturers started to widen their integrative activities with the aim to realize larger networks of vertically integrated companies to explore new efficiency potential beyond the boundaries of one enterprise and to support all phases of the production system lifecycle through a wide range of new services to deliver new customized functions and other benefits [8].

During the *transition phase from Wave 1 to Wave 2* a shift in focus from CM [9] to a more holistic view to address the entire product realization process through Cloud-based Design and Manufacturing (CBDM) [10] was observed. The inclusion of the design process into the I4 realm marked an important point in terms of expanding Cyber-physical Manufacturing to Cyber-physical Production Engineering (CPPE) [11]. It paved the way for enterprises adopting their strategies from delivering products to delivering product-service bundles [8] through an increase in Servitization and the generation of Product-Service Systems (S+PSS).

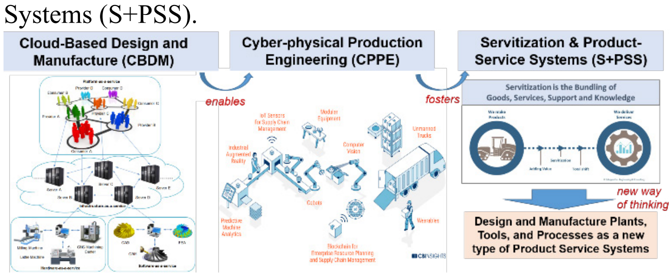

Figure 2: Industry 4.0 and Cyber-Technological Change [10, 12]

Throughout the second wave CBDM, CPPE, and S+PSS dominated research and development activities and served as enablers for advancing industrial production capability, see Fig. 2.

CBDM. Concepts for implementing CBDM systems on three different levels of automation (low, medium, and high) and three different levels of human dependency (high, medium, and low) were proposed. Until then, manufacturing was operating with a low-level of autonomy and a high dependency on humans. Some of early adopters of low-level automation are 3D Hubs, Fictiv, Opendesk, Maketine, and MFG.com [12].

CPPE. By design, CPPE is realized as an integrated system of intelligent techniques and manufacturing sub-systems (scheduling, control, maintenance, etc.) [11]. However, its success and efficiency become more and more dependent on new efforts in emerging Artificial Intelligence (AI) applications. AI dates from 1940s and it became popular with IBM`s AI-based chess playing computer program Deep Blue [13]. Today, AI is present in every field, such as disease diagnostics, robot control, and smart design to smart manufacturing [14]. AI is also considered to have great potential in terms of human-robot collaboration (HRC). HRC model data from sensors and field devices is transformed into knowledge after the application of appropriate machine learning models, and this knowledge is further transformed into actions using domain specific HRC decision modules [15].

S+PSS provide a unique combination for enterprises to identify and explore new business opportunities and to involve new customer segments by bundling products and services as a new mix of tangible and intangible elements designed and combined to increase the value for the customers and to grow their own market shares [8, 16, 17]. In this context dedicated methodologies for supporting business in their design of new PSS along a given product and its lifecycle were proposed, the majority of them were found to be too theoretical and hard to implement in practice. Others were found to be too specific, thus having limited application [18]. Charro and Schaefer in 2018 proposed to consider a manufacturing system as a special type of product, and with that to realize cloud manufacturing as a new type of product-service-system that would allow the acquisition of manufacturing capability and capacity as a service on demand [12].

In the mature adoption of I4 the need for cyber security and digital workforce become evident, and these are discussed in Sections 2.3 and 2.4.

2.3. Cyber security in Industry 4.0

I4 requires many components of an industrial organization's resources, such as devices and machinery found in manufacturing facilities, to be connected to a communication network with a path that, at some point, connects to the Internet [19]. Indeed, the unstoppable forces of I4 technologies ensure that future industrial organizations will have vast numbers of industrial systems that have network connections that lead to the global Internet [20]. As a result, cybersecurity technology and operations will play a critical role in the continued maturation of I4 [21, 22].

Currently, industrial and manufacturing organizations are integrating their Operational Technology (OT) and Industrial Control Systems (ICS) with their Information Technology (IT) systems. This is commonly referred to as IT/OT integration. IT/OT integration plays a key role for the realization and maturation of I4 [23].

Historically, OT and ICS were mostly isolated from IT networks, and, as a result, cybersecurity has not been a focus for OT and ICS. Now, however, practitioners and researchers have to consider the cybersecurity implications related to IT/OT integrations [23]. New technologies designed specifically for integrated IT/OT systems are scarce. Consequently, securing IT/OT systems currently revolves around retrofitting traditional IT cybersecurity technologies for OT systems, and this includes technologies such as network visibility, access control, identity management, detection, prevention, authentication, authorization, accountability, all of which seek to address the confidentiality, integrity, and availability triad of cybersecurity [24].

2.4. Industry 4.0 Workforce

With the advent of the fourth industrial revolution came a fear that higher levels of automation and digitization would lead to a significant reduction of manufacturing jobs. In 2019, the Annual Manufacturing Report revealed that 89% of their respondents agreed that while greater automation meant they could cut headcount, digitization would allow them to do more with same number of people [25]. In many ways, the technology themes surrounding Industry 4 at the time were not mapping onto the skillsets of the industry workforce and their fears were justified [26]. According to another study, evidence suggests that non-routine manual labor will be broadly unaffected, non-routine cognitive tasks have been complemented by computers, but middle-skilled routine tasks have been substituted by computers [27]. Manufacturing businesses have a growing need for a new type of engineers with digital skill sets. Unfortunately, today's university graduates or apprentices at large are not yet fully trained in these new competency areas and thus often underperform in the job market [25]. It is obvious that there is a discrepancy between the education pursued by students and the qualifications sought by employers and that today`s workforce is trained to only solve yesterday`s problems. In the UK`s and the US`s Education and Employers Taskforce lack of clarity and rapid change in the requirements of the labor market, and weak response to change of the higher education is identified as a cause for discrepancy [28]. Germany is widely regarded as being the forerunner in the I4 race. The answer is partly "reediness" and embracing I4 early on and open new training and education I4 centres [26, 27].

Although the design of manufacturing systems in the context of I4 facilitates an efficient data flow between different machines it does not yet deliver on the promise of I4 to seamlessly integrate supply chains, big data analytics applications or enterprise-level planning modules, delivering skilled workforce that will solve future problems. In the next section the research challenges and opportunities that has not received sufficient attention in the previous phase are presented.

3. State of the Art (Part 2)

3.1. Immediate challenges and rise of new opportunities in I4

For this phase insights into questions/concerns that have not been raised under the umbrella of Wave 2 are provided. The challenges are identified in regard to new and disruptive I4 business models required for new and disruptive technology, cybersecurity, workforce development, and other opportunities lying ahead of us.

As mentioned in terms of vertical integration a reasonable progress is achieved while horizontal integration remains a challenge. However, the challenge can be overcome with right approach to digital by embracing the vertical and horizontal integration [6]. Hence, design and manufacturing will go towards integration of CBDM with supply chain, and smart HRC manufacturing.

CBDM+SC4. The need for personalization and individualization of products and production processes along with tracking of goods from cradle to grave is anticipated to further increase. In addition to combining low-level RFID technology with high-level cloud-based tracking, future research and development efforts will be devoted to the realization of an I4-conform cyber-physical supply chain (SC4) where much emphasize will be put on recycling, reusing, and repurposing of goods and materials, see Fig. 3. Current challenges in regard to increased complexity and uncertainty will be countered by improved digital readiness, ranging from visibility to self-learning/autonomy [29].

Smart HRC Manufacturing. The future of Smart Human-Robot Collaborative (HRC) manufacturing lies in brain robotics where adaptive robot control will be achieved by using the brainwaves of experienced human operators [30]. The main concerns and limitation are the necessity for safety to be at higher Safety Integrity Level (SIL) and having to deal with outdated or incomplete standards for new technologies [15]. Another challenge is the lack of social awareness in HRC. There is a need for modelling emotional and social processes and the acquisition of individual or cultural profiles and their tuning to newly perceived changes. Further, the issue of ethics in HRC has also not yet been addressed in order to develop trustworthy relationship with respect and empathy from both sides [31]. Government regulation of Corporate Social Responsibility (CSR) for HRC in manufacturing is another important aspect to be addressed in future. New opportunities may include remote real-time monitoring and control with little or no delay, defect-free machining by means of opportunistic process planning and scheduling, cost-effective and secure predictive maintenance of assets, and holistic planning and control of complex supply chains [15].

3.2. I4 Cyber Security of Tomorrow

State of the art cybersecurity technology will have to evolve to address new security challenges that will accompany I4. For example, existing cybersecurity technology does not work well in terms of scale and dynamics. Existing cybersecurity technologies are based on static networks with reasonable scale (10s to 100s of thousands of nodes in the network). I4, however, will be characterized by very large and dynamic networks. Consequently, cybersecurity research that addresses these characteristics will be very important [24]. A sample of research topics that can address these forthcoming problems and should be pursued over the next five years include: (1) advanced and novel cybersecurity applications based on Data Science, Artificial Intelligence, and Machine Learning (DSAIM) [20]; (2) Automated and Autonomic Response (AAR) to Cyber Threats [32]; (3) Digital Twins with Advanced Simulation and Emulation (DTASE) [33]; and (4) Chaos Engineering in I4 [34]. Within this collection, AAR will be very important for real-time security of I4 systems, and AAR can be enabled by advancements in the other three components as applied to I4 cybersecurity [32].

3.3. I4 Workforce of Tomorrow

As previously discussed, there is a discrepancy between workforce qualifications sought by employers and workforce qualification delivered by mainstream education institutions. To alleviate this, more joint efforts between academia and industry are required [26].

The main challenges in delivering a digitally savvy workforce of tomorrow are rooted in today's outdated and inflexible education. Education should prepare students to solve tomorrow`s problem. It should be more focused and intensive, and perhaps degree programs should become shorter in the future (< 2 years) so that the knowledge of students will not be outdated by the time they graduate [25]. New means of delivering education online (MOOCs, etc.) are needed as well to increase access and reduce cost of provision at the same time.

In addition to the preceding, industrial strategy needs to go beyond the traditional view and baseline of increasing productivity, reducing expenses, and achieving shorter production cycles. Investment into talent and the fostering of creativity, empathy, and cognitive learning of employees may lead to new and innovative business strategies and management philosophies.

Another way of addressing the skill gap and attracting more people to manufacturing jobs is to improve the somewhat traditional perception that graduates have of manufacturing, away from being dirty to being high tech and cool. According to the Manufacturer, another option might be to embrace diversity, such as hiring more women, LGBT population, and other under-represented groups [35].

In general, the adaptation of non-technical career-sustaining competencies for generative learning is elementary for individuals to become lifelong learners who can upskill or even deskill along with technological change. Nevertheless, in terms of innovation, the need for human-human collaboration will remain important and continue to grow where new knowledge, creativity, critical thinking and empathy will be the primary competences required for success [36].

4. The Way Forward

In this section a strategic vision for the way forward are discussed and how the digital transformation in the context of I4 is anticipated to develop.

Strategic Vision. Over the course of the next 5 years it is anticipated that the design and manufacturing systems and processes to become fully integrated into End-to-End (E2E) decentralized ecosystems where digital transformation will be complete. An E2E decentralized ecosystem is a three-phase closed loop system. In the first phase, design, production, distribution, and end user are connected upstream to downstream, see blue arrows in Fig. 3. In the second phase, is the product life-cycle, see green arrows in Fig. 3. In the third phase, is the product afterlife from collection, recycle, remanufacture and ultimately redesign, see red arrows in Fig. 3.

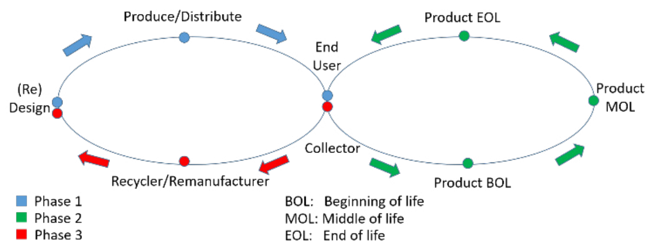

Figure 3: Decentralized Ecosystem

What are the challenges in digital transformation? There is a constant search for certainty in uncertain times where disruptions, man-made or caused by nature, will test decentralized ecosystems` agility, flexibility, resilience, and responsiveness [29]. As Charles Darwin stated: "It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change." Decentralized ecosystem that is flexible, robust and resilient is the one that will sustain in uncertain times. It is up to design engineers to design, and production and supply chain managers to maintain highly responsive and flexible decentralized systems that will quickly adapt to daily disruptions generated by external factors.

What are the dilemmas in digital transformation? Although many companies may feel the urge to conform Industry 4 in a rush, the old saying "You have to go slow in order to go fast." applies [6]. Digital transformation is a balancing act between two seemingly opposite concepts not a black-or-white perspective. Bavestrelli proposed 30 dilemmas that any company will be facing in the journey of digital transformation [37]. Furthermore, it is anticipated based on the size of company, stage of digital transformation, duration of digital transformation these dilemmas will be addressed differently, see Table 1.

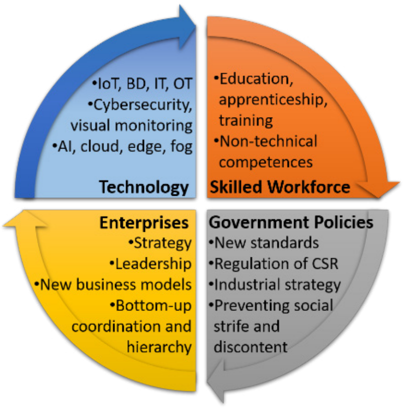

Figure 4: A strategic perspective on I4 over the next 5 years

Table 1: Dilemmas in Digital Transformation

Dilemma	In Short Run, Small Companies, Present	In Long Run, Big Companies, Future
Products vs. Services	Products	Services
Ownership vs. Access	Ownership	Access
IoT and Sensors vs. Digital Strategy	IoT and Sensors	Digital Strategy
Exciting Technologies vs. Customer Value	Customer Value	Exciting Technologies
Return on Investment vs. Leap of Faith	Return on Investment	Leap of Faith
Cost of Investing vs. Cost of Not Investing	Cost of Not Investing	Cost of Investing
Culture vs. Operations	Operations	Culture
Predict and Control vs. Learn and Adapt	Predict and Control	Learn and Adapt
Expectation of Success vs. Openness to Failure	Expectation of Success	Openness to Failure
Hierarchy vs. Autonomy	Top-down	Bottom-up
Coordination vs. Cooperation	Top-down	Bottom-up
Focus Inside vs. Focus Outside	Internal	External
Internal Digital Team vs. Outsourcing Digital Projects	Outsourcing Digital Projects	Internal Digital Team
Alone vs. Partnership	Alone	Partnership
Hire vs. Train	Train	Hire, Train
Learning vs. Doing	Doing	Learning
Human talent vs. AI talent	Human talent	Human and AI talent
Backlog vs. Innovation	Backlog	Innovation
Experience vs. Experiment	Experience	Experiment
Digital team vs. Business units	Business units	Digital team and Business units
Share vs. Hide	Hide	Share
Cloud vs. On-Premise	On-Premise	Cloud
Big data vs. Good data	Good data (any data)	Big data
Simplicity vs. Security	Simplicity	Security
Hype vs. Value	Hype	Value
Disrupt vs. Be disrupted	Be disrupted	Disrupt

What is the Strategic Perspective? The I4 vision promises benefits for all its stakeholders, customers, shareholders, suppliers and employees. However, there are many challenges to overcome, including the volume of data IoT generates, complexity of dispersed network structure, cyber-security, integration, and speedy, confident decision support, regulate CSR, and digital skilled workforce. Enabling a designer-manufacturer-supplier to move from where they are into the fast and agile future requires a strategic perspective, see Fig. 4. On technology level, see Quad. 1 in Fig. 4, it can be concluded that the technology surrounding I4 is there. Thus, the focus should be shifted to educating/training a digitally savvy workforce of tomorrow, and on setting new and required government policies and industrial strategies aimed at achieving the desired digital transformation. On an educational level, see Quad. 2 in Fig. 4, the workforce of today requires more digital skills to be prepared for the new types of jobs that are emerging. This transformation is anticipated to happen through joint efforts between academia and industry, leading to a transformed education system, retraining and upskilling of current workers, and the creation of bespoke apprenticeship programs. On government level, see Quad. 3 in Fig. 4, the focus should be on devising new policies for safety, ethics and social awareness, CSR regulations, and the preventing of social strife and discontent due to loss of blue-collar jobs to the process of automation [2]. On enterprise level, see Quad. 4 in Fig. 4, and regardless of company size there is a need to develop a digital infrastructure with dedicated strategy and leadership, and to increase sustainability efforts while maintaining economic growth.

5. Closure

About a decade ago Industry 4 was introduced as a bold vision and game changer for the domain of production engineering. This often called 4th industrial revolution is happing in four main phases as outlined in this paper, see Fig. 1. Initial efforts were mostly technology focused, aimed at devising architecture models for implementing cyber-physical systems for manufacturing. As this revolution in progress continued, it became clear that for it to reach its full potential other, previously ignored, aspects would have to be developed. They include the development of a new digitally savvy workforce, substantial investments into cybersecurity research and development, and new business strategies and disruptive business models that build on the disruptive technology behind

I4. To be successful in the long run, companies are advised to develop a holistic perspective on and strategy for I4-complient Production Engineering ecosystems rather than rushing the implementation of isolated point solutions for short-term gains. A limitation of the work presented lies in the fact that we did not specifically distinguish between SMEs of different sizes or their desired or afforded level of progressiveness. It would also be of interest to compare the UK manufacturing sector to those of other countries to get a holistic picture. This will be addressed in another forthcoming paper.

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