Digital Transformation beyond Industry 4.0 Maturity Stages

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Abstract
The majority of digital transformation maturity indices deal with the Industry level of digital maturity as the highest level. Digital transformation happens from the starting point, typically automation, to digitalization. Cyber-physical systems or systems of systems of cyber-physical systems are the highest levels of digital transformation in all indexes. Market analyzes show technologies have emerged since, and are now incorporated into Industry 4.0 at different stages of maturity. Literature review writes about technologies such as virtual reality, augmented reality, extended reality, or similar. Other technologies are additive manufacturing. Industry 4.0 visionaries rated by Gartner as such, PTC and Software AG, include additive manufacturing, blockchain, and new enterprise architecture to operate them in Industry 4.0. These technologies build on cloud platforms as a service, incorporate the digital twin and digital thread, and are used to operate cyber-physical systems, additive manufacturing, and sales bots. The goal of this research is to explore digital maturity indexes that go beyond the Industry 4.0 level with more advanced technologies. The methodology is an instrumental case study. The findings are that maturity stages go beyond the Industry 4.0 level via new technologies: additive manufacturing and blockchain and other dimensions of digital transformation as maturity stages: the outcome-based economy and blockchain. Whereas the Industry 4.0 model is a proposal in 2013, the goal of digital transformation is the intelligent enterprise or the digital enterprise. This is capable to generate disruptive innovation or facing disruption. The intelligent enterprise has an agile operating model. The intelligent enterprise can manage a VUCA environment. This article builds on the authors' article about digital transformation to Industry 4.0.

Keywords
Digital transformation; intelligent enterprise; additive manufacturing; blockchain; outcome economy; Industry 4.0; emerging technologies.

Introduction

Mainframe consultants (BCG, 2021; CapGemeni, 2011; Deloitte, 2020; Gartner, 2021; IBM Institute for Business Value, 2011; IDC, 2021; Markets & Markets, 2021; The World Economic Forum, 2020a, 2020b) and scientific resources (Porter & Heppelmann, 2014, 2015; Westermann et al., 2014a, 2014b) define digital transformation as the impact of changes on several dimensions of the organization driven by digital technology or other factors, such as the business models it enables.

The goal of digital transformation is not selling digital technology but architecting the intelligent enterprise or digital enterprise (IDC, 2021; SAP, 2021; The World Economic Forum, 2018). The intelligent enterprise can generate disruptive innovation or face disruptive innovation. The intelligent enterprise has an agile operating model. The intelligent enterprise combines operation and innovation to weather the VUCA world (NTTData, 2021).

Digital transformation, Industry 4.0, is reported in management literature as flexible value networks of cyber-physical systems working across the Internet of Things and Internet of Services (Kagermann et al., 2013). The initial vision of Industry 4.0 contains the technologies required to build and operate cyber-physical systems, such as cloud, analytics, digital twin (Porter & Heppelmann, 2014, 2015). Later studies mention subsequent technologies added to Industry 4.0 which include: virtual reality, augmented reality or extended reality; additive manufacturing at different stages of maturity (Alcacer & Macado, 2019).

IDC (2021a), the main market analyst, asserts 2021 is the timing of multiple innovations to the future intelligent enterprise. According to IDC (2021), years 2007-2015, the first stage of digital transformation is given by new technology and delivery model that give IT access at scale: cloud, mobile, social, big data. Platforms and communities (IDC, 2021) are the next stages, generating multiple innovations or innovations at scale, via technologies artificial intelligence, the internet of things, blockchain, natural interfaces. Autonomous systems bring hypercomplexity at scale (IDC, 2021): exponential artificial intelligence, quantum computing, biodigital integration.

Another important digital transformation institute, Gartner (2017, 2018, 2019, 2020), reviews emerging technologies per year. In 2018, Gartner added blockchain to the list of emerging technologies. In 2019, emerging technologies have included edge analytics, edge artificial intelligence, nanoscale 3D printing (Gartner, 2019). In 2020, emerging technologies that could be added to Industry 4.0 are digital twin of person; citizen twin; general artificial intelligence (Gartner, 2020). Gartner (2021) expects artificial intelligence technologies to mature differently in the next decade, as in Figure 1.

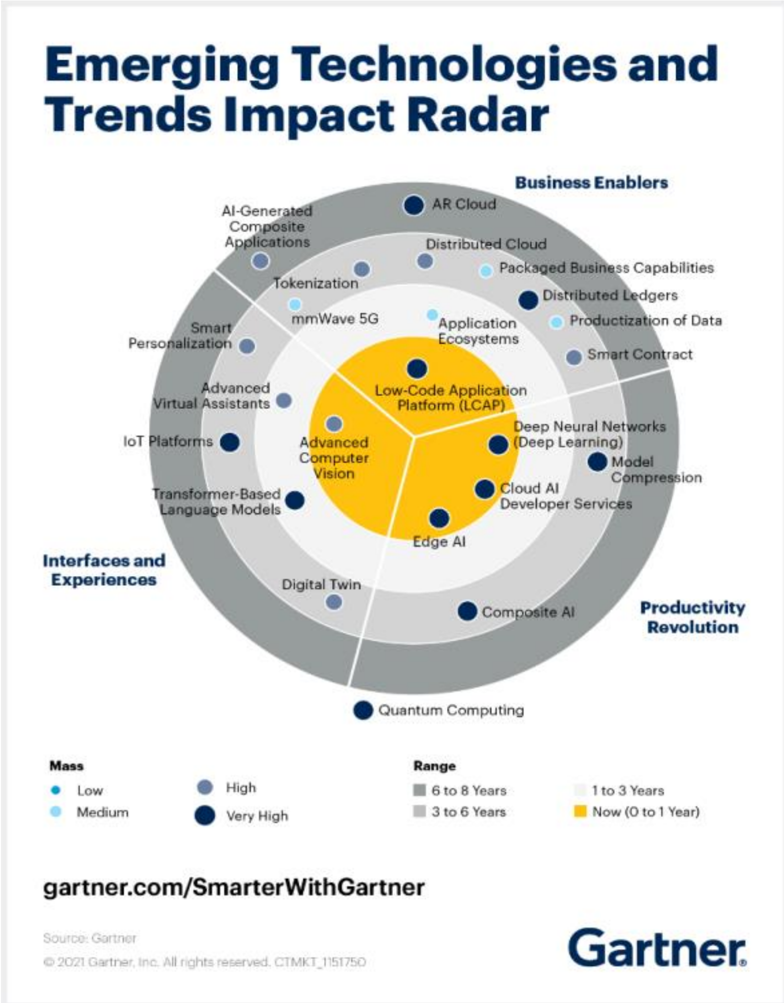

Figure 1. Gartner artificial intelligence maturity
(Gartner, 2021)

Gartner recognizes two visionaries for the Internet of Things market: PTC and Software AG. Software AG (2018) envisions an enterprise architecture with supply chain processes across the internet of things, cloud comprising the following processes and technologies: customer live time value by customer segment; market to cash processes, with technologies, augmented sales bots, and a digital twin; demand to operate processes, with technologies cobots logistics and cyber-physical systems; source to pay processes, with technologies 3D printing and digital rights; supplier spend analysis by product category. Accounting to profitability comprises blockchain and pay-per-use. Forecast to demand includes intelligent co-sourcing, integrated business planning, omnichannel intelligence. This enterprise architecture builds on Enterprise Resource Planning Suites. The next visionary in the Gartner magic quadrant is PTC. This article builds on the initial article that shows digital transformation to Industry 4.0. The ground is the emerging technologies and predicted business processes and business models which advance beyond cyber-physical systems and the systems of systems they form. The goal of this research is to explore, describe, and analyze the updates beyond the Industry 4.0 status in digital transformation maturity indices: the new maturity stages and the organizational dimensions involved. The impact is instrumental to management theory and practitioners' decisions. It is this impact that justifies the choice of methodology, a descriptive and instrumental case study. The article succeeds and complements the digital transformation to Industry 4.0 where most maturity indices, including Siemens, converge. As previously expounded, this is an original systematic approach.

Digital transformation maturity scales

In this view, the most popular Industry 4.0 maturity model proponents, Schumacher, Eroll, and Sihn (2016) maturity models are a tool for comparing current maturity level to the desired maturity level of an organization or process, by conceptualizing and measuring. Maturity systems increase their capabilities over time regarding the achievement of some future state. This definition is shared by other popular authors such as Proença and Borbinha (2016), and Mittal et al. (2018). According to Proença and Borbinha (2016), maturity models can be used as evaluation criteria and described as complete, perfect, or ready. Maturity models may be used from progression from the basic state to a more advanced final state. The role of maturity models is complex: audit; benchmark; process appraisal; organization appraisal; progress tracking; diagnostic (Proença & Borbinha, 2016). In Industry 4.0, maturity models are organizational capabilities, include a stream of objectives and sequential levels or stages (Sener et al., 2018). Maturity indices may be characterized by maturity levels and organizational dimensions involved in digital transformation. A literature review of the main maturity indices and digital transformation dimensions is performed in the following table. Maturity indices are used to shape digital transformation decisions and derive further digital transformation tools, such as the roadmap (Schumacher et al., 2019).

Table 1. The main maturity indices according to management consultants and scientific references

Year	Author	Maturity level	Dimension	Scale
2011	CapGemini	the combination of digital intensity and transformation management intensity: both low for beginners; high and low respectively for fashionistas; low and high respectively for conservatives; both high for digirati	business model: digitally modified business, new digital business, and digital globalization; operational or process: process digitalization, worker enablement, and performance management; customer experience: customer understanding, top-line growth, and customer touchpoints	
2011	Katsma et al.	supply chain systems moving towards the Internet of Things	business; application; information; technical infrastructure	ERP; ERP 2.0; SOA/ SAAS; IoT

2014	IBM	ad hoc, foundational; competitive; differentiating; breakaway	business strategy; information; analytics; culture and execution; architecture; governance	
2014, 2015	Porter and Heppelmann	monitoring, control, optimization, autonomy	business model, value chain, information technology architecture, corporate functions, relationships, processes, organizational structures, value	
2014, 2015	Lee et al.	smart connection-level; data to information conversion level; cyber level; cognition level; configuration level	Technology	
2015	IMPULS (Lichtblau, 2015)	beginner (new comer); intermediate (learner); experienced (expert); top performer (leader)	organizational strategy; smart factory; smart operation; smart products; data-driven services; employees	beginner (newcomer); intermediate (learner); experienced; expert; top performer
2015	Roland Berger	digital data; automation; connectivity; digital customer access	technology; technology enablers; customer propositions	detailed scale for each maturity model
2016	PWC	beginner; vertical integrator; horizontal collaborator; digital specialist	digital business models and customer access; digitization of product and service offerings; digitization of vertical and horizontal value chains; data and analytics as core capability; agile IT architecture; compliance, security, legal and tax; organization, employees, and digital culture	beginner; vertical integrator; horizontal collaboration; digital specialist
2016	KPMG	reactive participant; digital operator; ambitious transformer; smart digitalist	strategy; culture; monitoring; customer; organization and control; technology management; people and capabilities	transformation intensity; operational effectiveness
2016	Schumacher et al.		strategy; leadership; customers; products; operations; culture; people; governance; technology	1 – not implemented to 5 – fully implemented
2016	Ganzarain and Erasti	initial; managed; defined; transform; detailed business model	vision/envision; business/enable; actions/enact	detailed scale for every maturity level and dimension
2016	Jæger and Halse	3.0 maturity, initial; maturity; connected; enhanced; innovating; integrated; extensive; 4.0 maturity	Internet of Things	

2016	Qin et al.	digitalization; communication; standardization; flexibility; customization; real-time responsibility; predictive maintenance; decision making; early aware; self-optimization; self-configuration	factory; business; process; customers	transformation stages from initial technology to Industry 4.0
2016	Leyh et al. (SIMMI)	basic; cross; horizontal; vertical; total	vertical integration; horizontal integration; digital development; technology crossing	
2016	Westerman et al.	monitoring; communication and analysis; interpretation and services; adaption and optimization; cooperation	cyber-physical systems; information processing; communication system; human-machine-interface; data; services	
2016	Forrester Research	skeptics, adopters, collaborators, differentiators	cultural, organizational, technical, insights	score range based on scale
2017	Knowledge Exchange and Fraunhofer	the starting point, Industry 3.0; visibility, answering what happens?; transparency, answering what will happen?; predictability, answering what will happen?; adaptability, answering how can an autonomous reaction succeed?	smart solutions; smart innovation; smart networks; smart connected supply chains; smart production; data-driven business models; digital strategy and vision; digital strategy and vision; information technologies; resources; culture and mindset	framework; visibility; transparency; predictability; adaptability
2017	Acatech	computerization; connectivity; visibility; transparency; predictive capacity; adaptability	resources; informational systems; organizational structure; culture	detailed for each dimension and scale level
2017	Weber et al.	non-existent IT integration; data and system integration; integration of cross-life-cycle data; service-orientation; digital twin; self-optimizing factory	technology	
2017	Dreamy (De Carolis et al., 2017)	initial; managed; defined; integrated and interoperated; digitally oriented	processes; control and monitoring; technology; organization	
2017	Klötzer and Pflaum	digitalization awareness; smart networked products; the service-oriented enterprise; thinking in service systems; the	strategy development; customer offering; smart product or smart factory; complementary information technology; cooperation; structural organization;	

		data-driven enterprise	process organization; competencies; innovation culture	
2017	Gökalp et al.	incomplete; performed; managed; established; predictable; optimizing	asset management; data governance; application management; process transformation; organizational alignment	
2017	Lee et al.	analytic network process	leadership and strategy; product development; production planning; process control; quality control; facility management; logistics management; information system; facility automation; performance assessment	highly detailed assessment items
2018	McKinsey & Company	capabilities: data-driven insights; integrated customer experience; digital marketing; digitally-enabled operations; next-gen technology; digital enablers	strategy; culture; organization; capabilities	
2018	CapGemeni	beginners, conservatives, digital masters, fashionistas	the how: digital strategy, organizational structure; competencies; culture; IT ecosystem; network and data; the what: operational processes	computerization and connectivity; visibility and transparency; predictive power; adaptability and self-learning
2018	Deloitte	early; developing; maturing	strategy; leadership; workforce development; user focus; culture	early; developing; maturing
2018	European Commission	EU survey	digital economy; digital technologies; digital strategy; digital adoption; digital skills; digital transformation; digital investments; impact	scale from 0 to 100
2018	Canetta et al	absence; beginner; intermediate; experienced	strategy; processes; products and services; technologies; human resources	
2018	Akdil et al.	absence; existence; survived; maturity	smart products and services; smart business processes (research and development, production, marketing and sales, supportive operations); strategy and organization (business models, strategic partnerships, technology investments, organizational structure, and leadership)	
2018	Scremin et al.		business strategy, technology strategy, networking and integration, infrastructure for the Internet of Things,	detailed scale for each item

			analytical skills, absorbative capacity, benefits of Industrie 4.0 adoption, impact on efficiency	
2018	Sjodin et al.	connected technologies, structured data collection, and sharing, real-time process analysis and optimization, intelligent and predictive manufacturing	people, processes, technology	
2018	Sener and Gokalp	incomplete, performed, managed, established, predictable, optimized	asset management, data governance, application management, process transformation, organizational alignment	
2019	Accenture	champions; contenders; cadets	alignment; infrastructure; skills; partnership; measurement; cultural	champions; contenders; cadets
2019	Modrák and Šoltysová	conventional; starting, moderate; advanced; optimized	organizational product model; knowledge management; business strategy; product-related business models; innovation culture	additional requirements; product standardization; product modularity; process modularity; integration of product configurator into process planning; optimization of intelligent technologies and products
2019	Schumacher and Sihn		technology; products; customers and partners; value creation processes; data and information; corporate standards; employees; strategy; leadership	detailed scale for each dimension
2019	EDP Singapore, McKinsey & Company, Siemens, SAP, and TÜV SÜD (2019)	readiness assessment	process: operations, supply chain, product lifecycle; technology: shopfloor, enterprise, facility; organization: talent readiness, structure, and management	process: vertical integration; horizontal integration; integrated product lifecycle; technology: automation, connectivity, intelligence; workforce learning and development; leadership competency; inter and

				intracompany collaboration; strategy and governance
2020	BCG	innovate; incubate; scale and industrialize	strategy and aspiration; prioritized outcomes; people/ skills/ culture gap assessment; operating and governance principles; technology and data assets	
2020	Deloitte	low; medium; high	flexible, secure infrastructure; data mastery; digitally savvy, open talent networks; ecosystem engagement; intelligent workflows; unified customer experience; business model adaptability	
2021	EY	developing; established; leading	strategy, innovation, and growth; customer experience; supply chain and operations; technology; risk and cyber security; finance, legal, and tax; people and organization	

Methodology

This case study takes the Siemens example to describe, analyze and characterize a management tool for a new phenomenon, digital transformation. The case study is descriptive of the management tool. Literature review shows digital transformation indices are defined as an overview tool for the digital transformation phenomenon. In the digital transformation market, solution providers conceptualize maturity indices for internal use and external use at customers, where customers are important shares of the market. Siemens is a digital transformation supplier and leader in several markets. The maturity index is used internally at Siemens and in digital management consulting for digital transformation decisions at Siemens' customers (Siemens, 2021b). The digital maturity index may be used to diagnose digital maturity on the market or national level in quantitative research. Based on these arguments, the maturity index is assessed as instrumental in shaping decisions for Siemens' customers and diagnosing business activities for markets and nations. The evidence about the maturity index may pertain to maturity levels or the dimensions of digital transformation: digital technology, business processes, business models, innovation. Digital technology is explored individually: Internet of Things platform; Product Lifecycle Management software; artificial intelligence; cyber-physical systems; additive manufacturing; blockchain. Each of these technologies corresponds to digital transformation maturity levels. Evidence about business processes is related to each technology type and each stage of maturity. Innovation is treated as the strategy for the entire digital transformation, A large variety of Siemens' statements explore, describe and explain business processes and business models at each stage of digital maturity. This information is explored, described, analyzed in the case study. The instrumental approach takes the organizational dimensions and stages of maturity as argued in a variety of presentations and structures this information to construct Siemens' digital transformation maturity index in all its details.

Empirical analysis of the Siemens case – maturity levels of the customer offering

Overview of the Siemens case

Siemens is one of the key market players in the convergence of information technology and operational technology markets (Gartner, 2017). Siemens is several digital transformation technologies: cyber-physical systems, Product Lifecycle Management software, Internet of Things platforms. At Siemens, innovation in core technology electrification, automation, and digitalization on all vertical markets. Digitalization involves several technologies, which are used by all Siemens' vertical markets: manufacturing, infrastructure, mobility and to be carved out Energy and Healthineers. At Siemens, Advanta is a central unit in charge of digital transformation consulting (Siemens, 2021e, p. 32). Siemens Advanta enables companies to unlock the digital future by supporting their unique digitalization journey from start to finish (Siemens, 2021e, p. 32). Siemens has worked with PWC (2018) to support digital transformation consulting. The digital consulting framework contains the digitalization maturity scale as a key tool in managing digital transformation (Siemens, 2018c, p. 19; Siemens, 2020b). Digital transformation is at the heart of Siemens' businesses (Siemens, 2021e, p. 8). Leading in all businesses and shaping the digital transformation is intended from 2021 onwards.

Siemens' digitalization maturity scale

Siemens defines digitalization as leveraging digital technology for concrete customer benefits (Siemens, 2016a, p. 16; 2016b, p. 4; 2016c, p. 5). Digital transformation is defined as a change in the way value is created in an organization, via changes in business models, business processes, or organizational setup triggered by digital technology (Siemens, 2019i). In Siemens's digital maturity assessments, digital technology, business processes, and business models are the most frequently considered dimensions of change (Siemens, 2020g). Siemens works with PWC (2018). which defines the dimensions of digital transformation as strategic: digital strategy and business models; digital operating model, processes, structure, and culture; technological infrastructure and digital manufacturing processes. Digital maturity indexes are the first step in digital transformation consulting (Siemens, 2018c, p. 19; 2020b). At Siemens, the technology portfolio is called the digital enterprise (Siemens, 2021).

Siemens' maturity scale shows several stages of digital transformation to Industry 4.0. The first stage consists of connecting devices to the Internet of Things (CIMdata, 2019; Siemens, 2017b, p. 26; Siemens, 2017c, p. 13; Siemens, 2018c, p. 13; Siemens, 2019f, p. 21). Analytics technology moves the maturity scale to the next steps, descriptive, diagnostic, and predictive analytics (CIMdata, 2019; Siemens, 2017b, p. 26; Siemens, 2017c, p. 13; Siemens, 2018c, p. 13; Siemens, 2019f, p. 21). The next stage of digital maturity is closed-loop innovation (CIMdata, 2019; Siemens, 2017b, p. 26; Siemens, 2017c, p. 13; Siemens, 2018c, p. 13; Siemens, 2019f, p. 21). At this stage, the digital twin of product, production, and performance are united in a digital thread and feedback loop in closed-loop manufacturing (CIMdata, 2019; Siemens, 2017b, p. 26; Siemens, 2017c, p. 13; Siemens, 2018c, p. 13; Siemens, 2019f, p. 21). Technologies such as augmented reality, virtual reality also rely on the digital twin. The next technology is artificial intelligence, which brings cognitive capabilities; cyber-physical systems negotiate decisions as peer-to-peer forming systems of systems (CIMdata, 2019; Siemens, 2017b, p. 26; Siemens, 2017c, p. 13; Siemens, 2018c, p. 13;). The final stage in Industry 4.0 is self-optimizing systems (CIMdata, 2019, p. 21; Siemens, 2017c, p. 13; Siemens, 2018c, p. 13). On another scale, the level of digital maturity is reached by robotics and autonomous systems (Siemens, 2017c, p. 13; Siemens, 2018c, p. 13). Artificial intelligence may go beyond the level of the initial Industry 4.0 scenario (Siemens, 2017c, p. 13). Additive manufacturing is the next level of digital maturity (Siemens, 2017c, p. 13). The following level is not given by technology but disruption, new business models, and outcome economy (Siemens, 2017c, p. 13). An increased level of innovation leads to the next stage (Siemens, 2017c, p. 13). Blockchain (Siemens, 2017c, p. 13) takes technology to the next level of digital maturity (Siemens, 2017c, p. 13). Digitalization maturity (Siemens, 2018c, p. 13) is a function of digital twin and digital thread complexity.

Steps beyond the Industry 4.0 proposal: the additive manufacturing network

At Siemens (2020j), additive manufacturing has several degrees of maturity: traditional additive manufacturing, connected additive manufacturing, learning additive manufacturing, intelligent additive manufacturing, autonomous additive manufacturing. Connected additive manufacturing comprises: connected through MES, additive manufacturing network, digital twin and use build job stimulation and begins in 2017. Learning additive manufacturing involves: big data analytics, AM monitor, virtual storage, and machine learning and begins in 2018. Intelligent additive manufacturing: robots, virtual reality or augmented reality, artificial intelligence begins in 2020. Beyond 2025, additive manufacturing is autonomous for the Internet of Things.

Additive manufacturing is achieved by Product Lifecycle Management solution NX (Siemens, 2015d). There are several techniques of additive manufacturing (Siemens, 2017d): directed energy deposition, material extrusion, powder bed fusion, jetting (binder and material). They may use metal, plastic, ceramic, sand, composite (Siemens, 2017d, p. 3). In 2017, Simcenter (Siemens, 2017g) is added to NX and makes additive manufacturing apt for series production. Product Lifecycle Management (Siemens, 2018b, p. 2) systems and collaboration platforms, like the Teamcenter portfolio from Siemens PLM Software, are designed to handle the integration of data between enterprise resource planning (ERP). manufacturing operations management (MOM) and electronics design automation (EDA) systems and the accumulation of digital information created by each system in the digital thread. Additionally, PLM systems can link together the design and manufacturing systems to allow sharing of digital information between the two traditionally disconnected business operations. Teamcenter is integrated with MindSphere (Siemens, 2018b, p. 2). The Digital Collaboration Platform is used for additive manufacturing (Siemens, 2018d, pp. 26 –

33). Additive manufacturing functions are based on the digital twin of product, production, and performance (Siemens, 2018d, p. 29). For additive manufacturing, the Siemens Additive Manufacturing Network provides design consultation services and functions as well as manufacturing services for on-demand production. Distributed manufacturing platforms such as this are enabling companies to access production capacity for functional prototypes and serial production parts. Additive manufacturing is enabled by the MindSphere digital twin and digital thread (Siemens, 2018a, p. 6). Siemens' vision is an integrated end-to-end system for industrializing additive manufacturing (Siemens, 2018a, p. 6). Siemens industrializes advanced manufacturing with seamlessly integrated software and automation solutions, the digital twin, and digital thread (Siemens, 2019b; 2019h, p. 2). In 2019, Siemens uses additive manufacturing for electronic car batteries (Siemens, 2019c, p. 26). Siemens (2019h) launches an additive manufacturing network, an advanced cloud-based solution to foster collaboration and process orchestration between engineers, procurement, and suppliers of 3D printed parts. Siemens' network (2020d) is an online order-to-delivery collaboration platform for the industrial additive manufacturing community. MindSphere is combined with blockchain (Siemens, 2020; 2020e), giving food and beverages producers to utilize a secure, transparent ledger for every transaction and quality control check in a supply chain. The additive manufacturing network connects part buyers via the cloud with part suppliers, machine vendor, material vendor, software vendor, engineering consultancy (Siemens, 2020d).

Additive manufacturing (2018a) impacts products and manufacturing process transformation both. Products are reimagined with reduced weight, scan to product, expand performance, accelerate innovation cycles (Siemens, 2018a, p. 4; 2018e, p. 4). This causes a shift from conventional design to innovative DFAM. Reimagining products with the digital twin of the product means additive manufacturing gives customers the freedom to create forms that would have been impossible using conventional manufacturing methods (Siemens, 2021b). Reinventing manufacturing involves eliminating molding/castings/tooling; eliminating/simplifying assembly processes; reducing supply chains; affordable low volume production (Siemens, 2018a, p. 4; 2018e, p. 4). For instance, the additive manufacturing digital thread changes the process flow from the status quo: engineering, manufacturing, distribute, store, distribute to the industry target: engineering, distribute, manufacture, track (Siemens, 2018a, p. 4; 2018e, p. 4). In 2018 (Siemens, 2018e, p. 21). the process steps are requirements, generative design, adaption, performance validation, manufacturing validation, pre-processing and 3D printing, part finishing, and quality.

Reinventing manufacturing involves the digital twin of the production and the performance, where additive manufacturing optimizes the production process, setup, and configuration (Siemens, 2021b). Rethinking business involves individualization, personalization; zero inventory–on-demand printing; design anywhere; print anywhere; increase competitiveness (Siemens, 2018a, p. 4; 2021b). This also causes a shift from prototyping/experimentation to mainstream industrial production. The value of additive manufacturing: 65% fewer resources in the production process; 75% reduction of development time; infinite flexibility for the design of parts; 60% faster repairs; 50% reduction of lead time; 60% hydrogen in fuel mix (Siemens, 2019a). An example of a rethinking business is a personalized helmet made via 3D printing

(Siemens, 2020f; 2021b). Industrializing additive manufacturing (Siemens, 2020h) removes the barriers for mass adoption of industrial additive manufacturing by providing streamlined digital workflows to collaborate, plan and execute the additive manufacturing processes. The workflow collaboration involves order management, bidding, collaboration, part qualification, part preparation, planning and scheduling, execution, reporting, and shipping (Siemens, 2020h). Siemens (2020h) cocreates with an ecosystem of certified experts, suppliers, and technology specialists. Additive manufacturing supports distributed manufacturing business models (Siemens, 2020h). Siemens has used additive manufacturing during the Covid crisis to build spare parts for ventilators (Siemens, 2020i). Rethinking business means additive manufacturing enables flexible, fast, and efficient production (Siemens, 2020h). The process is perfect for custom production up to single-unit batches.

Disruptive innovation and the outcome economy

In 2021, at Siemens, digitalization involves weaving a digital thread through ideation, realization, and utilization, and making that digital thread of knowledge a proactive agent in driving customer business (Siemens, 2021d). With a fully optimized digital enterprise, customers are better equipped to initiate or respond to innovation. In 2015, Siemens (2015a, p. 5) claims smart innovations bring new business models in the internet age. Siemens' innovation strategy, smart innovation, is about weaving a digital thread of knowledge throughout the innovation process (Siemens, 2015b). The smart innovation strategy is about initiating or responding to disruptive innovation. Smart innovation is Siemens' strategy for Industry 4.0 and begins with the digital twin and digital thread in Product Lifecycle Management software. It goes on with smart networked devices and additive manufacturing (Siemens, 2015b). Siemens (2016b) notes that in Industry 4.0: products are getting smarter and more connected; smart innovations are transforming every industry; the products, business models, and legacy positions that once gave companies their competitive edge are no longer secure. Siemens (Siemens, 2017e, p. 4; 2017h, p. 9) claims a holistic view on digitalization is needed, as it impacts business models, value creation processes, products. New business models in the Internet age are disrupting complete markets (Siemens, 2015; 2018g, p. 3). Siemens notes that new innovative digital business models on business-to-customer markets are transforming the business-to-business world (Siemens, 2018d, pp. 2, 3). Siemens (2018f, p. 33) claims the IT/ OT convergence supports new business and collaboration models. The new business and collaboration models involve connected enterprises, connected products, connected consumers, connected customers, connected machines, connected research and development, connected suppliers. Siemens (2018g, p. 3) claims new business models in the internet age are disrupting complete markets. In 2017, Siemens uses two service business models, the pay-per-use business model and the pay-per-outcomes business model (Siemens, 2017f). In 2017, Siemens claim finance-enabled business models are developing to drive effective organizational and digital transformation (Siemens, 2017f). Siemens (2018g) claims the future belongs to output and performance-based business models. This may mean selling X as a service and paying for the usage and performance of industrial products. This makes the shift from a product-focused to a user-centric mindset (Siemens, 2018g, p. 4).

The new business models are data-driven (Siemens, 2018g, p. 9). Siemens (2019d) notes the Internet of Things is creating value and driving new business models. Business models change from linear to networks (Siemens, 2019d). The most sophisticated network business models are service business models (Siemens, 2019d). In 2019, Siemens' position remains to pay for outcomes in an Industry 4.0 business model (Siemens, 2019g). The additive manufacturing network is an online order-to-delivery collaboration platform for the industrial additive manufacturing community (Siemens, 2020a). This is on-demand manufacturing. Customers co-create with the help of a global supplier network of partners, suppliers, and customers. The additive manufacturing network is an ecosystem (Siemens, 2020a). The new technologies enable the digital supply chain (Siemens, 2020c). According to Siemens (2021c). the Internet of Things enables customers to develop entirely new business models, open up new sales channels and new sources of revenue, such as maintenance as a service; pay-per-use model; mass customization; application development. Already in 2017, Siemens (2017f) uses two service business models internally: pay for use and pay for outcomes. In the pay for use business models, pricing is based on a usage fee and customer contracts enclose customer benefits with clear stipulations. In the pay for outcomes business model, pricing is based on return on investment, and customer contracts enclose outcomes with clear stipulations.

Blockchain

Blockchain is a technology for distributed databases and a digital protocol for transactions between business partners – involving no intermediary such as a bank or a payment system such as PayPal (Siemens, 2017a). Blockchain is defined by Siemens as a decentralized open data repository (Siemens, 2018b, p. 9). Blockchain replaces centralized and proprietary databases (Siemens, 2018b, p. 9). At Siemens, in 2018, the MindSphere – PLM solution is integrated with blockchain by adding records of the digital twin to each physical part created with digital manufacturing technology. This allows the final assembled product to have a complete record of the manufacturing operations as well as the digital design and IP included in the completed product. The integration with blockchain enhances supply chain visibility (Siemens, 2018b, p. 9). Blockchain thereby aids the integration of decentralized manufacturing models (Siemens, 2018b, p. 9). Blockchain is used to trade energy (Siemens, 2017a). In 2017, Siemens expected blockchain to be mature enough for commercial use in the industrial context around 2022 (Siemens, 2017a). The following applications of blockchain are found: scaling and performance, response times for real-time applications and throughput rates for industrial-scale IoT structures; authenticated data flows, confidential data that originates, for example, from sensors, automation systems or external web services; confidentiality: a suitable balance between the necessary transparency concerning consensus and the required confidentiality with regard to content; security and compliance: new types of protocols for monitoring and intervention in blockchains –to report cases of fraud, for example; correctness of design and implementation: automated creation of secure blockchain software. In 2019, Siemens' cloud-based platform – MindSphere – provides the perfect means to capture data across supply chains (Siemens, 2019b; 2019h). Ready-made blockchain applications on MindSphere make it easy to subscribe and contribute (Siemens, 2019b;

Siemens, 2019h). Siemens has integrated MindSphere, Internet of Things, and blockchain (Siemens, 2019b; 2019h).

Conclusions

Several types of maturity indices in digital transformation exist. Some of them consider the technology stages to Industry 4.0 in the initial Plattform 4.0 scenario (Kagermann et al., 2013). The starting point is typically Industry 3.0, although the Qin et al. (2016) index considers a variety of starting points. Readiness assessments mentioned in the literature review show the attainment of the initial level for digital transformation to Industry 4.0. Technology grounded maturity stages show the technologies required to attend the Industry 4.0 level: the cloud, analytics, digital twin, artificial intelligence. Industry 4.0, cyber-physical systems, and the systems of systems they form are the final stage of digital maturity to be reached. As shown in the complementary article, digital maturity indices show the levels to reach the Industry 4.0 vision and the technologies that Porter and Heppelmann (2014, 2015) list as required to build smart connected products and the systems of systems they form.

Whereas the Industry 4.0 proposal dates 2013, since then, a series of emerging technologies have been incorporated in the Industry 4.0 vision at different levels of digital maturity that sometimes - with additive manufacturing, blockchain – go beyond the original vision. Gartner's visionaries Software AG and PTC consider additive manufacturing and blockchain as the next technologies involved in digital transformation. Siemens does the same. The Siemens scale goes on beyond the Industry 4.0 core level with maturity level disruptive innovation and the outcome economy. PTC notes that all levels of the digital transformation maturity indices depend on the technology advancement of the digital twin and digital thread. The Siemens example shows in detail how the Mindsphere platform as a service is progressively enhanced in terms of digital twin complexity to operate additive manufacturing systems and generate new business models. Blockchain is added to this platform. These solutions function together as enterprise architecture, as in the Siemens example and the Software AG example. Maturity indices have already been conceived that go beyond this level. Gartner and IDC envision beyond this level artificial intelligence will advance even further, for example via quantum computing. New digital transformation indices are required, that show digital transformation to the level of the digital enterprise, intelligent enterprise, or agile enterprise, that can initiate or face disruptive innovation. The goal of digital transformation is the capability to initiate or face radical innovation. The technologies incorporated in digital transformation are an evolutionary process. When tying this article to the complementary article, one may note Smart Innovation is Siemens' strategy for Industry 4.0 across all levels of digital maturity, that culminate in disruptive innovation. The indices are instrumental as they are conceived by digital transformation solution providers for customers, and therefore implicate shares of the global market and not the solution provider. Further research will use these indices in quantitative research about customer organizations, vertical markets, or geographical markets.

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