Decision Making in Manufacturing and Services
Vol. 12 • 2018 • No. 1–2 • pp. 17–31

Concept of Industry 4.0-Related Manufacturing Technology Maturity Model (ManuTech Maturity Model – MTMM)

Jarosław Gracel*, Piotr Łebkowski*

Abstract. The main objective of this article is to describe Industry 4.0 and the key manufacturing-technology-related technological and business challenges for manufacturing companies. The groups especially interested in the implementation of Industry 4.0 are the operations, technical, and production directors responsible for operational excellence of manufacturing plants, strategic development, and business continuity. Based on the latest Industry 4.0 and manufacturing technology market research, factories located in Poland are less technologically advanced than their counterparts in Western European plants. Accordingly, development of the model for assessing the current level of maturity for manufacturing technology related to the Industry 4.0 initiative becomes a relevant research task. In the article, key Industry 4.0-related technological areas will be described. Based on extensive research into international references and industrial consulting experiences in the industrial business consulting conducted in Polish manufacturing companies, the manufacturing technology ManuTech Maturity Model (MTMM) concept related to Industry 4.0 will be developed and presented. A substantial and innovative part of the article will be devoted to the adjustment of a proposed maturity model to specific features of the Polish industrial and manufacturing sector. This will be relevant due to the noticeable differences in the levels of technological advancement between the Western and Eastern Europe sectors.

Keywords: Industry 4.0, smart factory, manutech maturity model

Journal of Economic Literature codes: L6

Submitted: January 30, 2018

Revised: May 27, 2018

1. INTRODUCTION

In the last three decades, manufacturing technologies such as production automation systems, industrial robotics, manufacturing execution systems (MES), CAx systems, and enterprise resource planning systems (ERP) have been a relevant part of manufacturing businesses; however, their role has been only supportive. In the recently

* AGH University of Science and Technology, Faculty of Management, Krakow, Poland, e-mail: jaroslaw.gracel@gmail.com

DOI: https://doi.org/10.7494/dmms.2018.12.1-2.17

launched Fourth Industrial Revolution (known as Industry 4.0 in the manufacturing sector), its role will be elevated to the strategic level. Based on the research conducted by PwC (Geissbauer *et al.*, 2016), it is estimated that the share of investments in Industry 4.0 solutions will account for more than 50% of the planned capital investments for the next five years. Thus, German industry will invest a total of €40 billion in Industry 4.0 every year until 2020. Applying the same investment level to the European industrial sector, the annual investments will be as high as €140 billion. While countries with mature economies like Germany can afford a certain level of investment in Industry 4.0 initiatives, the economies of Central and Eastern Europe (like Poland's) will be exposed to significantly greater risks. The key risk (McKinsey & Company & Forbes, 2016) is connected with the digitization gap between Western European countries and Poland. Measured with the Digitization Index (McKinsey & Company & Forbes, 2016), the gap for the economy as a whole is 34%; however, this is 45% for the "advanced manufacturing" sector, and the "simple manufacturing" sector sits at 78% (!). Therefore, a formal Industry 4.0 Manufacturing Technology Maturity Model should be developed. The role of the model is to help top management answer critical questions such as, "What is the current level of technological advancement of the factory?" or "How should the manufacturing technologies be deployed to ensure the effective execution of a new Industry 4.0 strategy or new business models?" This paper is structured as follows. Section 1 contains Industry 4.0 definitions, its impact on manufacturing technology, and the related business/technical challenges. Section 2 introduces a definition of maturity models and presents a comparison of the existing Industry 4.0 and manufacturing technology-related maturity models. Section 3 contains the concept of the new ManuTech Maturity Model (or MTMM) with conclusions.

2. INDUSTRY 4.0 – DEFINITIONS

The first three industrial revolutions came about as a result of mechanization, electricity, and IT. Now, the introduction of the Internet of Things and Services into the manufacturing environment is ushering in the fourth industrial revolution. In the future, businesses will establish global networks that incorporate their machinery, warehousing systems, and production facilities in the shape of a cyber-physical system (CPS). Industry 4.0 emphasizes the idea of the consistent digitization and linking of all productive units in an economy (Gilchrist, 2014). The Industry 4.0 working group (Kagermann, 2013) developed recommendations to focus research efforts on three strategic topics:

- horizontal integration through value networks,
- end-to-end digital integration of engineering across the entire value chain,
- vertical integration and networked manufacturing systems.

The definition of Industry 4.0 given by Hermann *et al.* (2015) is as follows: Industry 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured smart factories of Industry 4.0, CPSs monitor the physical processes, create a virtual copy of the physical world, and make decentralized decisions. Over the IoT, CPSs communicate and cooperate with one another as well as humans in real time. Via the IoS, both internal and cross-organizational services are offered and used by participants of the value chain. While there are various initiatives at the global level around the future of manufacturing (e.g., Industrial Internet Consortium, Factory of The Future, Made in China), Industry 4.0 is the most consistent and, as it was developed in Germany, has the biggest influence on the European industrial market. The most repeatable Industry 4.0 components (Hermann *et al.*, 2015) are as follows: cyber-physical systems (CPS), the internet of things (IoT), the internet of services (IoS), and smart factory.

2.1. INDUSTRY 4.0 – IMPACT ON MANUFACTURING TECHNOLOGY

In-depth research into the literature has revealed many different views on key Industry 4.0 technologies, but the overall conclusion is that the impact of the Industry 4.0 initiative on the manufacturing technology landscape is significant. Accordingly, with the growing differentiation of customer requirements increasing the individualization of products, the level of manufacturing technology complexity will be constantly growing. The BCG (Rüßmann *et al.*, 2015) introduces nine pillars of Industry 4.0 technological advancement: big data and analytics, autonomous robots, simulation, horizontal and vertical integration, the industrial Internet of Things, cybersecurity, the cloud, additive manufacturing, and augmented reality. Many of the nine advances in technology that form the foundation for Industry 4.0 are already used in manufacturing; however, with Industry 4.0, they will transform production: isolated, optimized cells will come together as a fully integrated, automated, and optimized production flow leading to greater efficiencies and changing traditional production relationships among suppliers, producers, and customers as well as between a human and machine. The new technological characteristics of the industrial landscape will be as follows (Gilchrist, 2014): cyber-physical systems and marketplace, smart robots and machines, big data, new quality of connectivity, energy efficiency and decentralization, virtual industrialization, Factory 4.0 (a fully connected way of making things with key manufacturing technologies such as intelligent sensors, 3D printing/additive manufacturing, advanced materials, advanced manufacturing systems [CPS, full interconnected automation], robots, autonomous vehicles, cloud computing, and big data). The complement view (Chand *et al.*, 2016) distinguishes a number of disruptive technologies that will enable the digitization of the manufacturing sector:

- computational power,
- connectivity – big data/open data,
- the Internet of Things/M2M,
- cloud technology,
- analytics and intelligence,
- digitization and automation of knowledge work,
- advanced analytics,
- human-machine interaction – touch interfaces and next level of GUIs,
- virtual and augmented reality,
- digital-to-physical conversion – additive manufacturing,
- advanced robotics (e.g., human-robot collaboration),
- energy storage and harvesting.

The research into the advanced manufacturing technology trends (de Weck, Reed, 2014) identified seven categories: the nano-engineering of materials and surfaces, additive and precision manufacturing, robotics and adaptive automation, next-generation electronics, the continuous manufacturing of pharmaceuticals and bio-manufacturing, the design and management of distributed supply chains, and green sustainable manufacturing. The core manufacturing technologies relevant to manufacturing companies have been identified and should be taken into consideration in the maturity model development process.

Industry 4.0 and its core technologies such as secure plug & work solutions for the reconfiguration of machines, augmented reality-based assistance devices for workers, cyber-physical systems with inexpensive sensors to automatically collect data in value streams, machines and components, as well as machine learning and big data algorithms can be seen for car makers as enablers of transition towards flexible automation or scalable model-mix factories, for example (Wee *et al.*, 2015).

2.2. INDUSTRY 4.0 BUSINESS AND TECHNOLOGICAL CHALLENGES

Industry 4.0 brings numerous and different challenges; e.g., business, strategic, technological, and people-related ones. Based on international research (Geissbauer *et al.*, 2016), companies expect Industry 4.0 to favorably impact their revenue, costs, and efficiency. The additional revenue will come from digitizing products and services within the existing portfolio, new digital products, services, and solutions, offering big data and analytics as a service, personalized products and mass customization, capturing high-margin business through improved customer insight from data analytics, and increasing market shares of core products.

The lower costs and greater efficiency are expected to be generated by the following factors:

- real-time inline quality control based on big data analytics,
- modular, flexible, and customer-tailored production concepts,
- the real-time control of process and product variance,
- augmented reality and optimization by data analytics,
- predictive maintenance on key assets using predictive algorithms to optimize repair and maintenance schedules and improve asset uptime,
- vertical integration from sensors through MES to real-time production planning for better machine utilization and faster throughput times,
- horizontal integration as well as track-and-trace of products for better inventory performance and reduced logistics,
- digitization and automation of processes for a smarter use of human resources and higher operation speed,
- system-based real-time end-to-end planning and horizontal collaboration using cloud-based planning platforms for execution optimization.

In parallel to business improvement opportunities, certain business and technological challenges are connected.

According to Kagermann (2013), the greatest challenges connected with implementing Industry 4.0 will be:

– standardization,
– process/work organization,
– product (means technology) availability,
– new business models,
– security know-how protection (e.g., cybersecurity),
– a lack of specialist staff,
– research, training and CPD (continuing professional development).

The research (Bauer *et al.*, 2016) shows that six out of ten manufacturing companies face significant management barriers when working on Industry 4.0 implementation. The main barriers are connected with the level of progress in the Industry 4.0 implementation process and are as follows:

– The top five general barriers: difficulty in coordinating actions, the lack of courage to push through radical transformation, the lack of necessary talent, concerns about cybersecurity while integrating IT-OT systems, the lack of a clear business case that justifies investments in the underlying IT architecture,
– More-advanced manufacturers' barriers: concerns about data ownership, uncertainty about in- vs. out-sourcing and a lack of knowledge about providers, challenges of integrating data from disparate sources in order to enable Industry 4.0 applications.

While there are a lot of Industry 4.0 business challenges, the area of technological challenges should be addressed accordingly, as mass customization puts great strains on product developers and system designers (Fasth-Berglund, Stahre, 2013). A look at the development of computer science (CS), information and communication technologies (ICT), and manufacturing science and technology (MSC) reveals their parallel development (Monostori *et al.*, 2016). Therefore, convergence of the related manufacturing technologies dedicated to the virtual world and physical world will be expected. Should it come, the ability to build a future-proof architecture for manufacturing technology in a factory (or factory network) will become the critical skill.

The key priority (technology- and standardization-related) areas are as follows (Kagermann, 2013): standardization and open standards for a reference architecture, managing complex systems (e.g., planning models and explanatory models), delivering a comprehensive broadband infrastructure for industry, safety, and security (e.g., cybersecurity).

Other technological challenges are connected with the fact that Industry 4.0-related manufacturing technologies are at a different stage of maturity. Based on the Gartner Hype Cycle for Emerging Technologies research (Gartner, 2015), most of Industry 4.0-related technologies are at the "peak of inflated expectations" and "through of disillusionment" phases (but the situation has been changing dynamically). Only a few (e.g., 3D printing and virtual reality) are in the "slope of enlightenment" phase. It was principally the reliability and technical working order of machines that enabled the second (2.0) and third (3.0) industrial revolutions (i.e., the rise of manufacturing automation technology projects (Nowacki, 1953)).

In addition, the business justification of an Industry 4.0 investment should be developed properly. The lessons learned from the preparation for the third industrial revolution (production automation) showed that each manufacturing technology development phase and technological innovation has technological and economic aspects (Schulz, 1962). Therefore, it is important to formulate the following two questions:

1) Which manufacturing processes CAN be automated?
2) Which manufacturing processes SHOULD be automated?

2.3. MANUFACTURING TECHNOLOGY MATURITY IN POLISH MANUFACTURING SECTOR

Despite the fact that the Industry 4.0 initiative brings many opportunities to the Polish industrial market, many threats can be identified. The main threat list includes a lack of skilled workers and limited access to investment capital (Owerczuk, 2016). Moreover, the long-term historical competitive advantage of the Polish economy – its low-cost workforce – is beginning to run out. Poland has a significant digitization gap (McKinsey & Company & Forbes, 2016) in the manufacturing sector (45% in advanced manufacturing, 78% in simple manufacturing). Research into the level of automation in the Polish manufacturing sector (Hajkuś, Gracel, 2015) showed that only 15% of factories are fully automated and 76% are partially automated (which could mean that just one machine or even most of them are automated). Based on the industrial IT market research, almost 60% of the manufacturing companies in Poland gather shop-floor data manually, while 36% are prepared for automated data collection (Hajkuś, Gracel, 2015). An industrial robotics market research (IFR 2016) revealed that Poland had 28 robots per 10,000 employees in 2015. For the sake of comparison, Germany's robot density level is estimated at 292 per 10,000 employees. Moreover, only 32% of manufacturing and engineering companies have development programs for engineers in place (Gracel *et al.*, 2017).

An overview of the Polish manufacturing sector shows significant challenges in numerous dimensions. Polish enterprises (especially SMEs) are not aware of the forthcoming technological changes and, moreover, they do not understand the risk of overtaking production orders by their international partners (customers) due to the latter's higher efficiency gained from Industry 4.0 investments (Goetz, Gracel, 2017). These facts should be taken into consideration while developing the Manufacturing Technology Maturity Model related to Industry 4.0. The research shows that Polish managers still cope with Industry 3.0 challenges.

2.4. IMPACT ON DECISION MAKING AND IMPLEMENTATION CHALLENGES

The impact of Industry 4.0 on the manufacturing sector is of a strategic proportion. Kagermann (2013) identified various areas of potential; e.g.:

– meeting individual customer requirements,
– flexibility,

- responding to demographic change in the workplace,
- resource productivity and efficiency,
- a high-wage economy that is still competitive,
- creating value opportunities through new services,
- optimized decision-taking.

Industrie 4.0 (Kagermann, 2013) provides end-to-end transparency in real time, allowing for the early verification of design decisions in the sphere of engineering as well as a more flexible response to disruption and global optimization across all of a company's sites in the sphere of production. The decision-making process is supported from different perspectives; e.g., in terms of human resources or algorithms. In automotive manufacturing (Peters *et al.*, 2016), Industry 4.0 and autonomous driving (which could be called Mobility 4.0 in this analogy) use quite similar technologies such as various types of (optical) sensors, data fusion systems, and decentralized decision-making algorithms.

The successful implementation of an Industry 4.0 strategy requires the involvement of top- and mid-level management. There are three fundamentally different sources of an individual manager's poor to negative approach to implementing a strategy (Guth, Macmillian, 1986): perceived inability to execute a strategy, low perceived probability that the strategy will work, and the perception that the outcomes will not help achieve the individual goals. Thus, appropriate tools supporting a common understanding of the level of maturity of Industry 4.0 manufacturing technologies, etc., across all levels of organization should be developed.

3. OVERVIEW OF MANUFACTURING TECHNOLOGY MATURITY MODELS

Accoring to Paulk *et al.* (1993), maturity is defined as a specific process for explicitly defining, managing, measuring, and controlling the evolutionary growth of an entity. Maturity is related to the evolutionary progress in demonstrating a particular capacity or the pursuit of a certain goal from an initial state to the desirable final state. Kohlegger *et al.* (2009) defined maturity models as tools used to evaluate the maturity capabilities of certain elements and select the appropriate actions to bring the elements to a higher level of maturity. A maturity model (Proença, Borbinha, 2016) is a technique that has been proven to be valuable in measuring different aspects of a process or an organization. It represents a path towards an increasingly organized and systematic way of doing business in the manufacturing industry.

3.1. MATURITY MODEL ASSESSMENT DESIGN METHODOLOGIES

A review of the literature on maturity model design and development methodologies has helped us identify some references to leading topics. The most general approach to developing maturity models for the assessment of the Business Processes Maturity Model (BPMM) and Knowledge Management Capability Assessment (KMCA) described by De Bruin *et al.* (2005) proposes six model development phases: scope, design, populate, test, deploy, and maintain. The IT management-related Maturity Model development procedure (Becker *et al.*, 2009) comprises the following steps: problem definition, comparison of existing maturity models, determination of development strategy, iterative maturity model development, conception of transfer, and evaluation. The third design approach developed by Mettler (2010) recommends the performance of the following six steps: identify the need and specify problem domain, define the scope of the model application and use, identify the operationalization measures, implement the deployment and evaluation method, apply the model, evaluate the model structure and deployment method, synthesize the of design, and continuously learn.

For the purposes of the development of the MTMM, Becker's methodology has been chosen as the best recognized, up-close to the manufacturing technology domain, and practical application.

3.2. INDUSTRY 4.0 AND MANUFACTURING TECHNOLOGY RELATED MATURITY MODEL OVERVIEW

The Industry 4.0 context analysis performed in Section 1 has proven the relevance of the research subject and its relevance for the manufacturing technology domain. To develop the concept of a new maturity model (based on Becker's procedure), the second step of the process ("Comparison of existing maturity models") should be performed. During a thorough review of the literature (in English), more than 2000 references to maturity models have been identified, and more than 30 have been taken into consideration for further analysis. The review of Industry 4.0-related maturity models revealed ten key reference models (presented in Table 1).

Table 1. *Listing of maturity models related to Industry 4.0*

Model name	Delivered by	Domain	Target group	Year
CPS Maturity Model (Geisberger, Broy, 2012)	RWTH Aachen University	Cyber-Physical Systems	CTO, CIO	2012
The Digital Maturity Model 4.0 (Gill, Van Boskirk, 2016)	Forrester	Strategic Digitalization, Business Focus	CDO (Chief Digital Officer)	2016
The Connected Enterprise Maturity Model (Rockwell Automation, 2014)	Rockwell Automation	Industry (OT/IT Networks)	CIO, CTO	2014
Digital Compass maps Industry 4.0 (Wee *et al.*, 2015)	McKinsey & Company	Industry 4.0, Digitalization	CEO, CIO	2015
IMPULS – Industrie 4.0 Readiness (Lichtblau, Stich *et al.*, 2015)	VDMA, RWTH Aachen	Industry 4.0 Strategic	CEO	2015
Industry 4.0 / Digital Operations Self-Assessment (PwC, 2016)	PwC	Industry 4.0, Strategic	CEO, CIO	2016

Table 1 (cont.)

Industry 4.0 readiness and maturity model (Schumacher *et al.*, 2016)	Fraunhofer Austria	Industry 4.0 manufacturing strategy	CEO, CIO, R&D Director	2016
Supply Chain Visibility Maturity (Gartner, 2015)	Gartner	Supply Chain	Supply Chain Director, CIO	2015
3DP (3D Printing) Maturity Model (Mueller, Karevska, 2016)	EY	Additive Manufacturing	CEO, CTO	2016

For the purposes of ManuTech Maturity Model (ManuTech MM, MTMM) development, they have been evaluated. The most comprehensive approach to the subject has been embedded into the following three models: IMPULS – Industrie 4.0 Readiness (Lichtblau, Stich, 2014), Industry 4.0/Digital Operations Self-Assessment (PwC, 2016), and the Industry 4.0 readiness and maturity model (Schumacher *et al.*, The research into the "Industry 3.0" maturity models helped us identify models of automation maturity, such as 19 levels of manufacturing process automation (Nof, 2009) or the Level of Automation (LoA) assessment methodology (Fasth-Berglund, Stahre, 2013).

No model focused on the assessment of manufacturing technology maturity levels was found during our review of the literature. After the review and (six) workshops with managers of Polish manufacturing companies, the gaps in the current models have been identified and discussed below.

3.3. IDENTIFIED GAPS IN EXISTING MATURITY MODELS

While Industry 4.0 is an innovative initiative, there are some areas still undefined, imprecise, and uncertain. According to Mettler (2011), while building a maturity assessment model for a highly innovative phenomenon, the justificatory knowledge to base upon is weak or missing and the principles of form and function are unclear, as no dominant design prevails. Furthermore, the cases necessary from which to derive the maturity levels and recommendations may be missing as well.

During our gap analysis of the existing maturity models, the following difficulties were identified:

- While the literature review has identified Industry 4.0-related maturity models, the gap analysis shows areas in the models that should be extended; e.g., deep technology insights. Moreover, a maturity model dedicated to Manufacturing Technology was not found during the review.
- Industry 4.0 Maturity Models are mainly focused on the strategic levels of companies. Operational and technology levels have been overlooked.
- Current models present a superficial approach to those manufacturing technologies that are to be the core components of the manufacturing companies aiming to develop manufacturing processes ready for mass customization.

- Current models do not take into consideration a current level of "technologization" (e.g., level of production automation or robotic density) of the industrial market/companies. It creates a risk to the applicability in less advanced economies (like Poland's).
- Current models do not relate to the manufacturing technologies from Industry 3.0 that are still and will be the core part of manufacturing companies. To retrieve the comprehensive maturity assessment results, a combination of core technologies should be used. An Industry x.0 approach should be developed.
- Current models focus on the assessment of a general set of Industry 4.0-related technologies without focusing on the specificity of a certain industry (e.g., automotive, electronics, food processing, and others). In the new model, manufacturing technologies should be grouped into a sets of general technologies (Industry 4.0-related) and specific technologies (based on industry-best practices).
- Workshops carried out with manufacturing companies in Poland focused on assessing the Industry 4.0 technological readinessresulted in the demotivation of the managers. The reason is that people do not like to be said to be "totally not aligned" with Industry 4.0 from a technological perspective.
- Current models are focused in the majority on top (C-level) managers, which is important to start the Industry 4.0 initiative; however, the research showed that middle management involvement is a crucial aspect in the implementation of the strategy. Accordingly, the new maturity model should pay special attention to this fact.
- Current maturity models do not refer to the maturity of the assessed technologies. This creates a risk of the underestimation of CAPEX (Capital Expenditure), TCO (Total Cost of Ownership), applicability, and reliability of the technologies. This should be taken into consideration during the new model development.

The assessment of the gaps in the existing maturity models can contain some faults because of a lack of accessibility to a detailed description of the models and intellectual property issues (since the consulting companies and research institutes that provide the service of maturity assessment to organizations restrict access to their intellectual property (Willaert *et al.*, 2007)). However, the gap analysis performed forms a basis for the development of a new maturity model in the manufacturing technology domain (the ManuTech Maturity Model, or MTMM).

4. CONCEPT OF MANUFACTURING TECHNOLOGY MATURITY MODEL (MTMM)

4.1. MODEL ASSUMPTIONS

The comprehensive gap analysis resulted in the development of the concept of the new maturity model related to the manufacturing technology (with an Industry 4.0 correlation). The model will be named the "ManuTech Maturity Model," or briefly, the MTMM.

While conducting the "Determination of development strategy" model design step (based on Becker's methodology), the main assumptions that should be taken into consideration (based on Section 2.4 – Gap analysis) are as follows:

1) The model should focus on the operational level of the manufacturing technologies with respect to its strategic alignment.
2) The target group of the model will be middle management of manufacturing companies.
3) The model will be focused on the maturity of manufacturing technologies with key supporting items (such as strategic alignment, cybersecurity, knowledge management, people, & culture).
4) The mix of core manufacturing technologies will be selected based on the relevance for a specific industry, reference Industry 4.0 technologies, and research in the advanced manufacturing technology domain.
5) The model should refer to the Industry 4.0 design principles (Hermann *et al.*, 2015): interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity.
6) The model will contain a reference to the maturity of technologies included (e.g., based on Technical Readiness Level (TRL) or Gartner's hype-cycle)
7) Special attention will be paid to the practicality and applicability of the model.

Following the best practices in the development of the maturity models, the structure of the model should contain:

– the maturity levels (Levels 1 to 4, with 1 being the lowest and 4 – state-of-the-art),
– the dimensions,
– the method of application,
– the method of representations.

4.2. MTMM CONCEPT

Based on the workshops and interviews with experts and middle managers of manufacturing companies (in Poland) conducted by the authors over the last five years, the concept of the MTMM structure has been developed.

The concept includes the following eight dimensions with maturity items assigned to them (details are presented in Table 2): core technologies, people & culture, knowledge management, real-time integration, infrastructure, strategic awareness & alignment, process excellence, and cybersecurity. These dimensions have been proposed as the most comprehensive conceptualization of maturity, combining the theoretical and practical perspectives of the topic. The authors propose two methods of application: self-assessment or assessment by an external expert, and a numerical method of representation with visual radar charts. After processing Becker's "Iterative maturity model development" step, the model will be transformed into the assessment tool and tested with the manufacturing companies of a specific industrial sector. Due to the fact that numerous existing maturity assessment models have faced applicability problems, the practical verification of the concept will be a crucial step in the development of the ManuTech Maturity Model.

Table 2. *MTMM dimensions and maturity items*

Dimension name	Dimension description and items
Core technologies	Dimension defining to what extent the company uses modern manufacturing technologies relevant to its particular industry and general set of Industry 4.0-related technologies. **General:** predictive analytics, advanced automation of machines, advanced scheduling, etc. **Industry domain specific:** robotized palletizing, additive manufacturing (e.g., 3D printing) for components, process traceability, etc.
People & culture	Dimension defining to what extent the organizational culture is able to absorb modern manufacturing technologies. This covers the organizational culture openness to innovation, technology/technical competences of employees, employee empowerment level, employee satisfaction level, level of technical culture, ability to use modern technologies, and engineer development systems, for example.
Knowledge management	Dimension defining to what extent the company is able to gather, store, process, and distribute knowledge concerning critical processes and systems; e.g., engineering standards, manufacturing systems documentation, applications, source codes, etc.
Real-time Integration	Dimension defining to what extent the company integrated its critical business processes related to value chains (horizontal, vertical, end-to-end engineering). Integration is assessed as the level of data flow automation, for example. The sample business processes being assessed are as follows: Production Management – Maintenance Management, R&D – Production Management, Production Scheduling – Production Management, Customer Order – Production Scheduling.
Infrastructure	Dimension defining to what extent the company's infrastructure is capable of hosting and supporting manufacturing technology implementation and integration. The aspects being assessed are as follows: high-speed internet access at shop floor, energy meters with Ethernet connections, machine readiness to automated data access, etc.
Strategic awareness & alignment	Dimension defining to what extent the company is able to lead manufacturing technology transformation in the strategically defined directions; e.g., leadership competences development level, digitization strategy, business case in place, etc.
Process excellence	Dimension defining to what extent the company is advanced in the deployment of process excellence methodologies and tools in production management, maintenance management, quality management, supply chain management, production planning, continuous improvement, etc.
Cybersecurity	Dimension defining to what extent the company is prepared to prevent and process cybersecurity risks; e.g., security policy for IT/OT, cybersecurity vulnerability audits, active protection equipment, passive protection tools, etc.

A sample application of the MTMM model where the model is used to assess current state of the factory maturity and designing of desired state is presented in Figure 1. This approach is a widely used and accepted method of setting objectives by manufacturing managers.

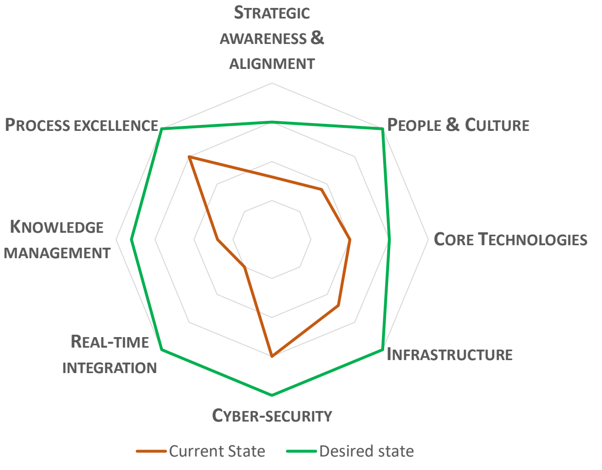

Fig. 1. *Sample visualization of current/desired state analysis with MTTM model*

5. CONCLUSIONS

To summarize, the paper presents a comprehensive analysis on the subject of Industry 4.0 with the definitions, impact on manufacturing technology, and related business/technological challenges. Moreover, it introduces a definition of maturity models and presents a comparison of the existing Industry 4.0- and manufacturing technology-related maturity models. Finally, it presents the concept of the new manufacturing technology-related MTMM. The main conclusions are as follows:

- The rationale behind the concept of the MTMM is strong, having been based on both an in-depth literature examination and direct interviews with the target group (middle managers of manufacturing companies) in Poland.
- The concept of the models addresses the main gaps identified during the comparisons of existing maturity models in the Industry 4.0/Manufacturing technology domains.
- The concept of the MTMM creates a solid foundation for building a practical and long-term tool for the assessment of maturity in the manufacturing technology domain.
- The MTMM will be evaluated and tested in a specific manufacturing company to prove its practicality and applicability.
- The MTMM is based on the generic term “Manufacturing Technology”; with this approach, it can be applied to various types of industries and multiple technologies. Consequently, on the MTMM model, a long-lasting and Industry x.0 independent maturity assessment can be based.

REFERENCES

Bauer, H., Baur, C., Mohr, D., Tschiesner, A., Weskamp, T., Mathis, R., 2016. Industry 4.0 after the initial hype. *McKinsey Digital.*

Becker, J., Knackstedt, R., Pöppelbuß, J., 2009. Developing Maturity Models for IT Management. *Business & Information Systems Engineering*, 1(3), pp. 213–222.

Chand, S., Davis, J., Gilchrist, A., Wee, D., Kelly, R., Lopez, R., 2016. Industry 4.0. *McKinsey & Company*, 8(1), pp. 4–7.

De Bruin, T., Freeze, R., Kaulkarni, U., Rosemann, M., 2005. Understanding the Main Phases of Developing a Maturity Assessment Model. In: *Australasian Conference on Information Systems (ACIS)*, pp. 8–19.

Fasth-Berglund, Å., Stahre, J., 2013. Cognitive automation strategy for reconfigurable and sustainable assembly systems. *Assembly Automation*, 33, pp. 294–303.

Gartner Inc., 2015. *Hype Cycle for Emerging Technologies.* Gartner Inc.

Geisberger, E., Broy, M. (eds.), 2012. agendaCPS – Integrierte Forschungsagenda Cyber--Physical Systems. *Acatech STUDIE*, vol. 1, Springer, Berlin–Heidelberg.

Geissbauer, R., Vedso, J., Schrauf, S., 2016. Industry 4.0: Building the digital enterprise. PwC, pp. 1–36.

Gilchrist, A., 2014. Industry 4.0. Roland Berger (March).

Gill, M., Van Boskirk, S., 2016. The Digital Maturity Model 4.0. Forrester.

Goetz, M., Gracel, J., 2017. Przemysł czwartej generacji (Industry 4.0) – wyzwania dla badań w kontekście międzynarodowym. *Kwar*, 1(51), pp. 217–235.

Gracel, J., Stoch, M., Biegańska, A., 2017. *Inżynierowie Przemysłu 4.0. (Nie)gotowi do zmian?* Astor, Kraków.

Guth, D.W., Macmillian, C., 1986. Strategy Implementation versus Middle Managements Self-interest. *Strategic Management Journal*, 7(4), pp. 313–327.

Hajkuś, J., Gracel, J., 2015. *W jakie technologie inwestują firmy produkcyjne w Polsce?* Raport. Astor, Kraków.

Hermann, M., Pentek, T., Otto, B., 2015. Design Principles for Industrie 4.0. Scenarios: A Literature Review. Working Paper 1/2015. Technische Universität Dortmund.

Kagermann, H., 2013. Securing the Future of German Manufaturing Industry. Recommendations for implementing the strategic Initiative Industrie 4.0. In: *Acatech, Final Report of the Industrie 4.0 Working Group* (April), pp. 4–7.

Kohlegger, M., Maier, R., Thalmann, S., 2009. Understanding maturity models results of a structured content analysis. *Proceedings of IKNOW '09 and ISEMANTICS '09*, (September), pp. 51–61.

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., Schmitt, K., Schmitz, E., Schröter, M., 2015. IMPULS – Industrie 4.0 Readiness. Impuls-Stiftung des VDMA, Aachen.

McKinsey & Company & Forbes, 2016. *Cyfrowa Polska* (report). McKinsey & Company.

Mettler, T., 2010. *Supply Management im Krankenhaus – Konstruktion und Evaluation eines konfigurierbaren Reifegradmodells zur zielgerichteten Gestaltung.* Dissertation der Universität st. Gallen, Hochschule für Wirtschafts-, Rechts- und Sozialwissenschaften (HSG) zur Erlangung der Würde eines Doktors der Wirtschaftswissenschaften. Sierke Verlag, Göttingen.

Mettler, T., 2011. Maturity assessment models: a design science research approach. *International Journal of Society Systems Science*, 3(1/2), pp. 81–98.

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sinh, W., Ueda, K., 2016. Cyber-physical systems in manufacturing. *CIRP Annals – Manufacturing Technology*, 65(2), pp. 621–641.

Mueller, A., Karevska, S., 2016. EY's Global 3D printing Report 2016 – Executive Summary. Ernst & Young GmbH.

Nof, S., 2009. *Handbook of Automation. Computation and Control.* Springer Verlag.

Nowacki, P., 1953. Automatyzacja procesów wytwórczych. *Przegląd Elektrotechniczny*, 1, pp. 1–17.

Owerczuk, M., 2016. *Przemysł 4.0. Szansa czy zagrożenie dla rozwoju innowacyjnej gospodarki?* Boston Consulting Group.

Paulk, M.C., Curtis, B., Chrissis, M.B., Weber, C.V., 1993. Capability Maturity Model for Software, Version 1.1. Technical Report CMU/SEI-93-TR-024 ESC-TR-93-177, February 1993, Carnegie Mellon University.

Peters, S., Chun, J.-H., Lanza, G., 2016. Digitalization of automotive industry – scenarios for future manufacturing. *Manufacturing Review*, 3(1), pp. 6–7.

Proença, D., Borbinha, J., 2016. Maturity Models for Information Systems – A State of the Art. *Procedia Computer Science*, 100(2), pp. 1042–1049.

PwC, 2016. The Industry 4.0 / Digital Operations Self-Assessment. `https://i4selfassessment.pwc.de/i40/landing/` (accessed on: 16 August 2017).

Rockwell Automation, 2014. The Connected Enterprise Maturity Model, 12. `http://www.rockwellautomation.com/rockwellautomation/innovation/connected-enterprise/maturity-model.page?` (accessed on: 16 August 2017).

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., Harnisch, M., 2015. *Industry 4.0. The Future of Productivity and Growth in Manufacturing Industries.* Boston Consulting Group.

Schulz, Z., 1962. *Efektywność ekonomiczna automatyzacji produkcji przemysłowej.* Państwowe Wydawnictwo Naukowe, Warszawa.

Schumacher, A., Erol, S., Sihn, W., 2016. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. *Procedia CIRP*, 52, pp. 161–166.

Weck, O.L. de, Reed, D., 2014. Trends in Advanced Manufacturing Technology Innovation. In: Locke, R.M., Wellhausen, R.L. (eds.), *Production in the Innovation Economy*, pp. 235–262.

Wee, D., Kelly, R., Cattel, J., Breunig, M., 2015. *Industry 4.0 – How to navigate digitization of the manufacturing sector.* McKinsey & Company.

Willaert, P., Van den Bergh, J., Willems, J., Deschoolmeester, D., 2007. The Process-Oriented Organization: Holistic View Developing a Framework for business process orientation maturity. In: *Business Process Management – 5th International Conference, BPM 2007, Brisbane, Australia, September 24–28, 2007, Proceedings.* Alonso, G., Dadam, P., Rosemann, M. (eds.). Springer-Verlag, Berlin – Heidelberg.