acatech STUDY

Industrie 4.0 Maturity Index

Managing the Digital Transformation of Companies

Update 2020

Günther Schuh, Reiner Anderl, Roman Dumitrescu, Antonio Krüger, Michael ten Hompel (Eds.)

German Research Center for Artificial Intelligence

fir an der RWTH Aachen

Fraunhofer

ptc

HEINZ NIXDORF INSTITUT UNIVERSITÄT PADERBORN

TECHNISCHE UNIVERSITÄT DARMSTADT

it's owl

INDUSTRIE 4.0 MATURITY CENTER

acatech NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

acatech STUDIE

Industrie 4.0 Maturity Index

Managing the Digital Transformation of Companies

Update 2020

Günther Schuh, Reiner Anderl,
Roman Dumitrescu, Antonio Krüger,
Michael ten Hompel (Eds.)

The acatech STUDY series

The reports in this series present the results of the Academy's projects. The STUDY series provides in-depth advice for policymakers and the public on strategic engineering and technology policy issues. Responsibility for the studies' contents lies with their editors and authors.

All previous acatech publications are available for download from www.acatech.de/publikationen.

Contents

Foreword

Companies are constantly being confronted with new challenges. Platforms are changing the face of traditional markets, new technologies and working methods are resulting in shorter innovation cycles, while climate change and resource scarcity demand solutions that are compatible with a circular economy. In order to remain competitive, it is becoming more and more important for companies to develop competencies such as resilience, responsiveness and adaptability.

Industrie 4.0 marks the onset of the fourth industrial revolution. The factory of the future will be hyperconnected, smart and autonomous. It will also be characterised by high adaptability and optimal resource utilisation. Industrie 4.0 can deliver huge benefits for the productivity and profitability of German manufacturing industry, manufacturing equipment suppliers and enterprise software companies. While collaboration between man and machine will call for greater flexibility and adaptability, it also offers people the prospect of better, more fulfilling jobs.

The use of digital technologies and the comprehensive networking of objects, devices and machines in the course of the implementation of innovative Industry 4.0 solutions also contribute to improvements in the speed of reaction and the resilience of companies in order to better overcome unexpected developments such as the coronavirus crisis. In addition, real-time networking simplifies operation while maintaining physical distance.

In recent years, companies have become increasingly aware of Industrie 4.0's potential. Companies see Industrie 4.0 as an opportunity to gain a competitive advantage so that they can become market leaders or strengthen their existing market leadership. However, although more and more companies now perceive the digital transformation as an opportunity, 58% of the board members surveyed by BITKOM Research in 2019 admitted that their company was lagging behind with regard to digitalisation. The demand from businesses for clear guidance accounts for the overwhelming success of the original acatech STUDY *Industrie 4.0 Maturity Index*, which was published in 2017.

Many Industrie 4.0 related projects within companies are currently launched in response to rising competitive pressures and growing need to tackle the digital transformation. However, a large proportion of these projects are failing. This is often because they don't contribute significantly enough to the corporate objectives, are too strongly focused on individual technologies, or cannot be scaled up. Accordingly, to add value and support the company's goals, individual pilot projects must be scalable and must deliver positive results within a short timeframe.

In our experience, companies can benefit significantly from carrying out an integrated, systematic analysis of their own individual digital transformation that is focused on meeting their corporate objectives. The strategic implementation of Industrie 4.0 in accordance with the systematic approach outlined in this study facilitates not only the introduction of pilot projects but also the company-wide scale-up that is essential in order to add value.

The fact that companies are buying into this approach and are increasingly having positive experiences with Industrie 4.0 is reflected in the huge interest surrounding our original study. In this new *Update 2020* edition, we revisit the original guidelines for a successful digital transformation in manufacturing companies, addressing both their business strategy and the four structural areas of resources, information systems, culture and organisational structure. Concrete examples from companies that have successfully implemented this approach and achieved a positive impact on their performance are provided in our companion publication *Using the Industrie 4.0 Maturity Index in Industry – current challenges, case studies and trends*.

I hope you enjoy reading this new edition.

Prof. Henning Kagermann
Chairman of the acatech Board of Trustees

Management Summary

The term Industrie 4.0 has been used since 2011 to describe the widespread integration of information and communication technology in industrial manufacturing. As well as increasing the efficiency of processes, routines and systems, Industrie 4.0 offers companies new opportunities to differentiate their products and services. However, it is not enough to address the developments associated with the fourth industrial revolution from a purely technological perspective. Digitalisation also requires companies to transform their organisation and culture so that they can become as flexible and adaptable as possible. There is no denying that advanced technologies make it possible to access a much wider range of data – artificial intelligence techniques in particular enable powerful new data analysis and evaluation processes. However, the ability to implement these technologies and leverage the data's underlying potential is just as dependent on a company's organisational structure and culture. The ultimate goal is to become a learning, agile company capable of adapting continuously and dynamically to a disruptive environment – particularly to better overcome unexpected developments like the coronavirus crisis.

The acatech Industrie 4.0 Maturity Index presented in the first edition of this study in 2017 was developed with the aim of providing companies with a guide to introducing and implementing the required digital transformation process. This guide comprises a six-stage maturity model in which the attainment of each development stage delivers additional benefits. The acatech Industrie 4.0 Maturity Index focuses on the four key structural areas of resources, information systems, organisational structure and culture. Each of these areas has two fundamental principles attached to it. The main challenge for companies wishing to implement Industrie 4.0 is to put these principles into practice by developing the various specific capabilities described in this study. Doing so will allow them to generate knowledge from data, enabling rapid decision-making and adaptation processes throughout every part of the company. The acquisition of this agility provides companies with a significant competitive advantage in a disruptive environment. Manufacturing companies can use the acatech Industrie 4.0 Maturity Index to develop a digital roadmap that is precisely tailored to their individual needs and can be used to implement Industrie 4.0 and transform the company into a learning, agile organisation. Since its publication in 2017, the methodology outlined in the acatech Industrie 4.0 Maturity Index has been widely used by companies, both to gain a better understanding of Industrie 4.0 and in particular to guide the development of their own digital transformation process. The fact that the study has been downloaded ten thousand times from the websites of acatech and its project partners bears witness to this widespread interest.

This 2020 update revisits the acatech Industrie 4.0 Maturity Index, incorporating a number of editorial changes into the STUDY together with updates to some of the illustrations.

Our new companion publication *Using the Industrie 4.0 Maturity Index in Industry – current challenges, case studies and trends* presents examples of companies that are already successfully using the Maturity Index in practice. As well as reviewing the status quo, it identifies current trends, areas requiring urgent action and future challenges.

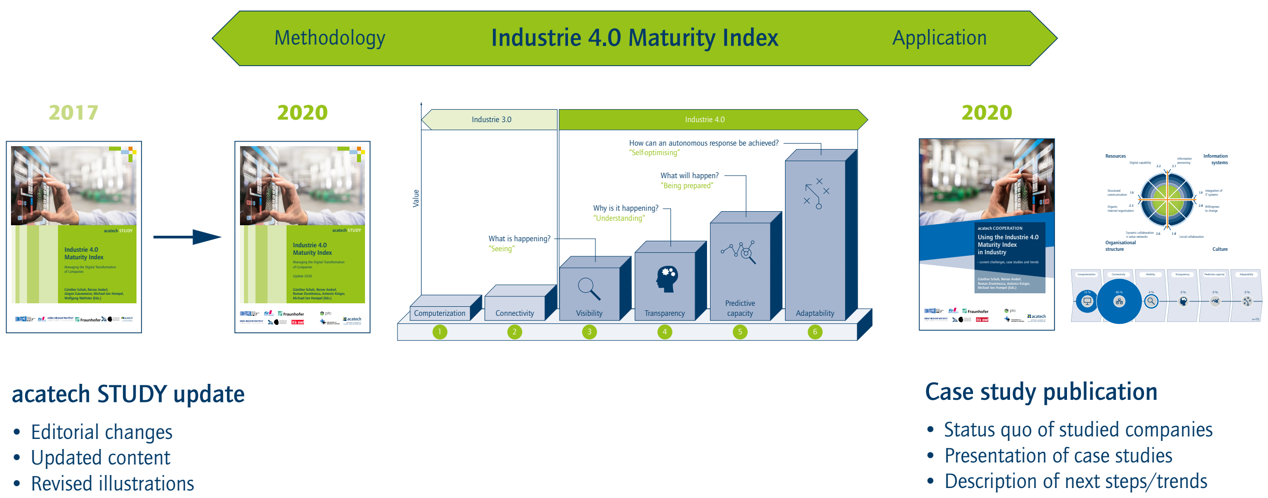


Figure 1: Study update and companion publication with case studies (source: authors' own illustration)

Project – First version of the study 2017

Project management

- Prof. Dr.-Ing. Günther Schuh, RWTH Aachen/acatechh

Project group

- Prof. Dr.-Ing. Reiner Anderl, Department of Computer Integrated Design (DiK), Technical University of Darmstadt/acatech
- Prof. Dr.-Ing. Jürgen Gausemeier, Heinz Nixdorf Institute, Paderborn University/acatech Executive Board member
- Prof. Dr.-Ing. Günther Schuh, RWTH Aachen University/acatech
- Prof. Dr. Michael ten Hompel, Fraunhofer Institute for Material Flow and Logistics IML, TU Dortmund University/acatech
- Prof. Dr. Dr. h.c. mult. Wolfgang Wahlster, German Research Center for Artificial Intelligence, DFKI/acatech

Experts

- Ulrich Ahle, FIWARE Foundation e.V.
- Dr. Sebastian Busse, Unity AG
- Prof. Dr.-Ing. Roman Dumitrescu, Heinz Nixdorf Institute, Paderborn University; Fraunhofer Institute for Mechatronic Systems Design IEM
- Nampuraja Enose, Infosys Ltd.
- Kent Eriksson, PTC Inc.
- Dr. Ursula Frank, Beckhoff Automation GmbH & Co. KG
- Dr. Bertolt Gärtner, TÜV SÜD AG
- Markus Hannen, PTC Inc.
- Dr. Florian Harzenetter, PTC Inc.
- Dr. Andreas Hauser, TÜV SÜD Asia Pacific Pte. Ltd.
- Craig Hayman, AVEVA Group
- Howard Heppelmann, PTC Inc.
- Claus Hilger, independent consultant , Hilger Consulting
- Ulrich Kreitz, itelligence AG
- David Kronmüller, KONUX GmbH
- Dr. Ravi Kumar G.V.V., Infosys Ltd.
- Udo Lange, itelligence AG
- Dr. Jan Stefan Michels , Weidmüller Interface GmbH & Co. KG
- Jeff Miller, Inspirage, LLC
- Gordon Mühl, Huawei Technologies
- Prof. Dr.-Ing. Boris Otto, Fraunhofer Institute for Software and Systems Engineering ISST, TU Dortmund University
- Felisa Palagi, Internet Creations
- Dr. Thomas Roser, PTC Inc.
- Sudip Singh, ITC Infotech
- Prof. Dr. Volker Stich, FIR e.V. at RWTH Aachen
- Klaus Strack, itelligence AG
- Erwin Tanger, Atos IT Solutions and Services GmbH
- Dr. Adeline Thomas, itelligence AG
- Frank Tüg, PTC Inc.
- Werner Varro, TÜV SÜD Product Service GmbH
- Kevin Wrenn, PTC Inc.
- Rene Zölfl, PTC Inc.

Consortium partners/project team

- Dr. Tilman Becker, German Research Center for Artificial Intelligence, DFKI
- Dr. Anselm Blocher, German Research Center for Artificial Intelligence, DFKI
- Isabel Bücker, McKinsey & Company
- Marvin Drewel, Heinz Nixdorf Institute, Paderborn University
- Andreas Faath, Computer Integrated Design (DiK), Technical University of Darmstadt
- Dr. Tobias Harland, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Dr. Mario Hermann, TU Dortmund University
- Gerd Herzog, Evonik Technology & Infrastructure GmbH
- Dr. Philipp Jussen, Schaeffler Technologies AG & Co. KG
- Ulrike Krebs, FIR e. V. at RWTH Aachen
- Dr. Maximilian Lukas, Vaillant Group
- Benedikt Moser, FIR e. V. at RWTH Aachen
- Katrin Pitz, Computer Integrated Design (DiK), Technical University of Darmstadt
- Dr. Daniel Porta, German Research Center for Artificial Intelligence, DFKI
- Dr. Jan Reschke, SMS group GmbH
- Dr. Sebastian Schmitz, Industrie 4.0 Maturity Center at RWTH Aachen Campus

- Moritz Schröter, FIR e. V. at RWTH Aachen
- Moritz Weber, Computer Integrated Design (DiK), Technical University of Darmstadt
- Lucas Wenger, FIR e. V. at RWTH Aachen
- Dr. Thorsten Westermann, Miele & Cie. KG
- Dr. Violett Zeller, FIR e. V. at RWTH Aachen

Project coordination

- Christian Hocken, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Dr. Alexander Werbik, WEVENTURE GmbH
- Dr. Johannes Winter, acatech Office

Funding and project support

The study was funded by partners from industry. acatech would like to thank the following companies:

- Infosys Ltd.
- PTC Inc.
- TÜV SÜD AG
- Technology Network it's OWL and affiliated companies
  - Atos IT Solutions and Services GmbH
  - Beckhoff Automation GmbH & Co. KG
  - HARTING Technology Group
  - itelligence AG
  - UNITY AG
  - Weidmüller Interface GmbH & Co. KG

Project – Update of the study 2020

Project management

- Prof. Dr.-Ing. Günther Schuh, RWTH Aachen University/ acatech

Project group

- Prof. Dr.-Ing. Reiner Anderl, Department of Computer Integrated Design (DiK), Technical University of Darmstadt
- Prof. Dr.-Ing. Roman Dumitrescu, Heinz Nixdorf Institute, Paderborn University; Fraunhofer Institute for Mechatronic Systems Design IEM
- Prof. Dr. Antonio Krüger, German Research Center for Artificial Intelligence, DFKI/acatech
- Prof. Dr.-Ing. Günther Schuh, RWTH Aachen University/ acatech
- Prof. Dr. Michael ten Hompel, Fraunhofer Institute for Material Flow and Logistics IML, TU Dortmund University/ acatech

Experts

- Mark Gallant, PTC Inc.
- Markus Hannen, PTC Inc.
- Dr. Florian Harzenetter, PTC Inc.
- Howard Heppelmann, PTC Inc.
- Prof. Dr.-Ing. Boris Otto, Fraunhofer Institute for Software and Systems Engineering ISST, TU Dortmund University
- Prof. Dr. Volker Stich, FIR e.V. an der RWTH Aachen
- Kevin Wrenn, PTC Inc.
- Rene Zölfl, PTC Inc.

Consortium partners/project team

- Nazanin Budeus, Fraunhofer Institute for Material Flow and Logistics IML,
- Stefan Gabriel, Fraunhofer Institute for Mechatronic Systems Design IEM
- Marcel Hagemann, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Dr. Tobias Harland, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Jonas Kaufmann, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Jörn Steffen Menzefricke, Heinz Nixdorf Institute, Paderborn University
- Laura Mey, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Felix Optehostert, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Dr. Daniel Porta, German Research Center for Artificial Intelligence, DFKI
- Jannik Reinhold, Heinz Nixdorf Institute, Paderborn University
- Dr. Sebastian Schmitz, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Yübo Wang, Computer Integrated Design (DiK), Technical University of Darmstadt
- Lucas Wenger, FIR e. V. at RWTH Aachen
- Dr. Violett Zeller, FIR e. V. at RWTH Aachen

Project coordination

- Christian Hocken, Industrie 4.0 Maturity Center at RWTH Aachen Campus
- Joachim Sedlmeir, acatech Office
- Dr. Johannes Winter, acatech Office

The first version of this acatech STUDY was realized in 2017 with the support of Infosys Ltd., PTC Inc., TÜV SÜD AG, and the Technology Netzwork it's OWL and affiliated companies. We would like to thank PTC Inc., the Industrie 4.0 Maturity Center, and all professional partners for supporting the acatech Industrie 4.0 Maturity Index – Update 2020.

1 Introduction

The term "Industrie 4.0" was introduced in 2011 by the Communication Promoters Group of the Industry-Science Research Alliance to describe the widespread integration of information and communication technology in industrial production. The "4.0" alludes to how this trend's potentially revolutionary impact follows directly in the footsteps of the three previous industrial revolutions. Since 2011, a number of initiatives addressing the theme of digitally connected industrial production have sprung up around the world, for example the Industrial Internet Consortium in the US and the Industrial Value Chain Initiative in Japan.

The value creation potential of Industrie 4.0 for German manufacturing industry is estimated to be between 70 and 140 billion euros for the period to 2025 alone.[1] One of the main reasons is that many companies currently fail to appreciate the concrete benefits of Industrie 4.0. This is confirmed in a study by the Federal Ministry for Economic Affairs and Energy (BMWi) which identifies a lack of transparency regarding the benefits as one of the key obstacles to the introduction of Industrie 4.0, especially among small and medium-sized enterprises (SMEs). Together with the purported technological and financial uncertainties and excessively long implementation timeframes, the result is that for the time being German companies are proving extremely reluctant to invest.[2]

At present, the only measures implemented in many companies involve occasional pilot projects that are in fact more akin to technological feasibility studies. Projects like this are unable to demonstrate the full potential of Industrie 4.0, since they overlook key aspects of its implementation such as a company's organisational structure and culture. As a result, the changes are often only evolutionary in nature. Unfortunately, they also often fail to reflect the organisation's actual processes or to meet the real needs of manufacturing companies. Consequently, there are limited examples of transformational change either within individual enterprises or at the level of the economy as a whole.

At the same time, manufacturing companies, especially in Germany, are faced with increasingly competitive markets. The dynamic environment and resulting complexity mean that businesses need to make faster and better decisions if they are to remain competitive over the longer term. Current business practices often fail to address this challenge and run the risk of losing the control point of their core business. Decision-making processes can take weeks or even months and decisions are often based on a intuitive feeling rather than on hard data. Product development processes issue product requirements documents and set out detailed product specifications without a comprehensive understanding of the customer's needs. When something new is learned, it is only possible to make limited modifications to the development or manufacturing process and even this can be very time-consuming. Many employees and decision-makers regularly have to spend time searching and waiting for the right information. These are just a few examples to illustrate the major shortcomings that currently exist and the potential for a far-reaching transformation.

The chief economic potential of Industrie 4.0 lies in its ability to **accelerate corporate decision-making and adaptation processes**. This applies both to processes for driving efficiency in engineering, manufacturing, services and sales and marketing and to the focus of entire business units or changes to the business model. This study defines Industrie 4.0 as "real-time, high data volume, multilateral communication and interconnectedness between cyber-physical systems and people". The availability of huge quantities of data and information at affordable prices and – if necessary – in real-time, enables a better understanding of how things relate to each other and provides the basis for faster decision-making processes. Coupled with the right organisational structure, this allows companies to react faster to their customers' increasingly dynamic markets, be faster to develop new products that are more precisely tailored to their customers' requirements and bring these products to market exponentially faster. Interconnectedness of the technological and in particular the organisational components makes it possible to achieve the agility that is the key capability required by companies in Industrie 4.0. This transformation into an agile company is the most important opportunity for manufacturing companies in Industrie 4.0. Of course, companies will only be able to leverage the full potential of Industrie 4.0 if they implement the practices described above across all of their business processes and if data and data analysis are visible across the entire enterprise.

1 | See Auer 2018, p. 8.
2 | See BMWi 2015, p. 37.

The agile company in Industrie 4.0

Agility is a strategic characteristic that is becoming increasingly important to successful companies. In this context, agility denotes the ability to implement changes in the company in real-time, including fundamental systemic changes to the company's business model, for example.

Consequently, the significance of Industrie 4.0 lies in the key role of information processing in enabling rapid organisational adaptation processes. The faster an organisation can adapt to an event that causes a change in its circumstances, the greater the benefits of the adaptation. In this context, the umbrella term "event" may relate to a range of different business decisions. Events may be short-term in nature, for instance a production line breakdown, or medium- to long-term, for example a change in product requirements and the associated modifications to the product design itself, to the manufacturing process and to related processes in purchasing, quality and service.

At present, when an event occurs in a company there is a delay before detailed insights about the event become available. This means that there is also a delay in taking the corresponding decisions and (counter-)measures (see Figure 2). One of the reasons is that the relevant information systems are not sufficiently integrated to enable end-to-end data processing, from data capture to analysis.

Industrie 4.0 capabilities help manufacturing companies to dramatically reduce the time between an event occurring and the implementation of an appropriate response (see Figure 3). In practice, this means that, for example, changes in customer requirements based on field data can be incorporated even during a product's manufacturing process because the company possesses the agility to adapt to the new situation. As a result, the customer can be supplied with a product tailored to their exact requirements in a significantly shorter period of time and higher quality.

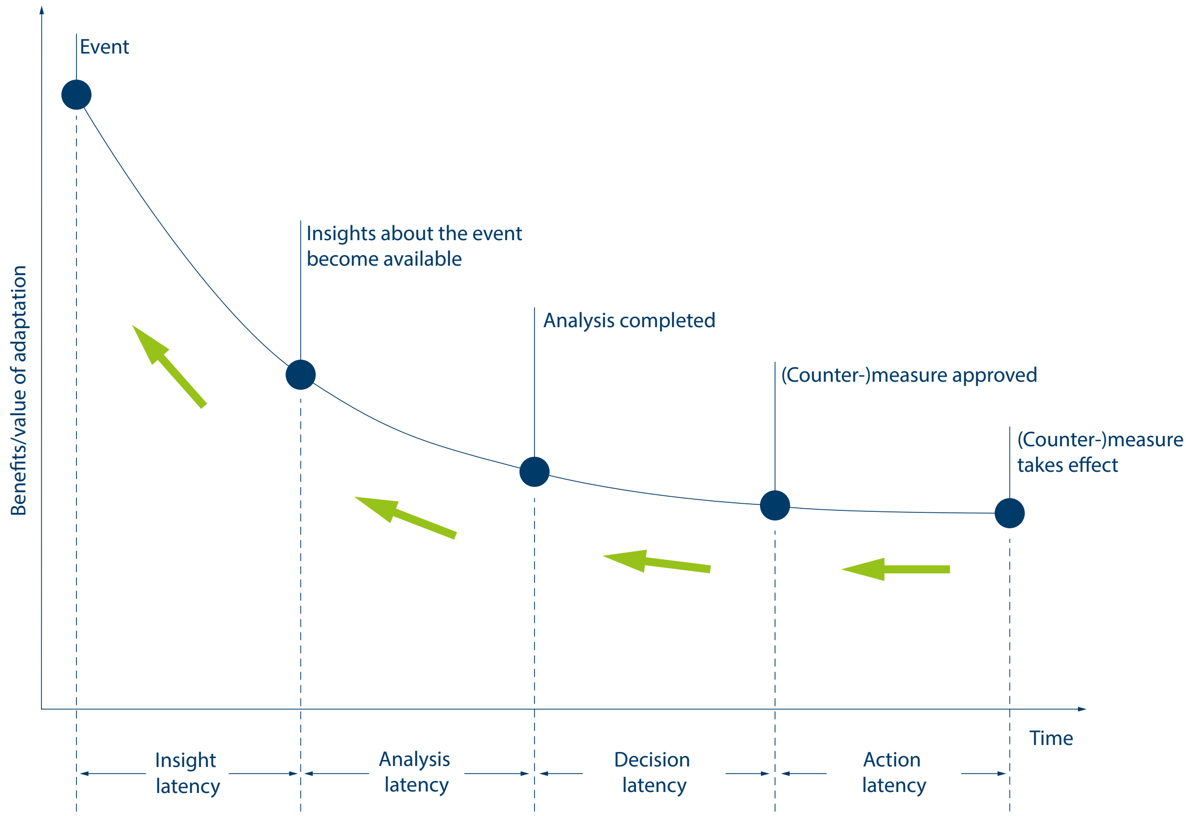


Figure 2: Corporate adaptation processes (source: based on Hackathom 2002; Muehlen/Shapiro 2010)

Augmented Reality

One example to reduce latencies is Augmented Reality: Imposing digital information on a real world environment creates a new dimension of use cases. Digital information such as 3D CAD models or data captured by sensors or calculated by IT systems can be placed in context to a real world environment. This creates a dramatically enlarged information flow from the IT world to e.g. an operator or a service technician. As a result any task performed by these roles will be completed faster with less errors, since they can be provided with the exact relevant data. Old ways to convey such information e.g. by manuals or phone calls can be eliminated.

A variety of different technologies must be deployed to achieve this target state. In addition, relevant information have to be available by open isolated data silos. However, these technological changes are not enough on their own. New approaches to the company's organisational structure and culture are also crucial to a successful transformation. For instance, the entire organisation must be prepared to support and shape these continuous changes.

The goal of the transformation is to create a learning, agile company capable of continuously adapting to changing conditions thanks to the use of the relevant technologies, organisational learning and decision-making processes that take advantage of high data quality that is available more rapidly. The learning, agile company is able to occupy digital control points. The acatech Industrie 4.0 Maturity Index provides manufacturing companies with guidance both on how to forge their own individual path towards becoming a learning, agile company and on which measures will deliver concrete benefits.

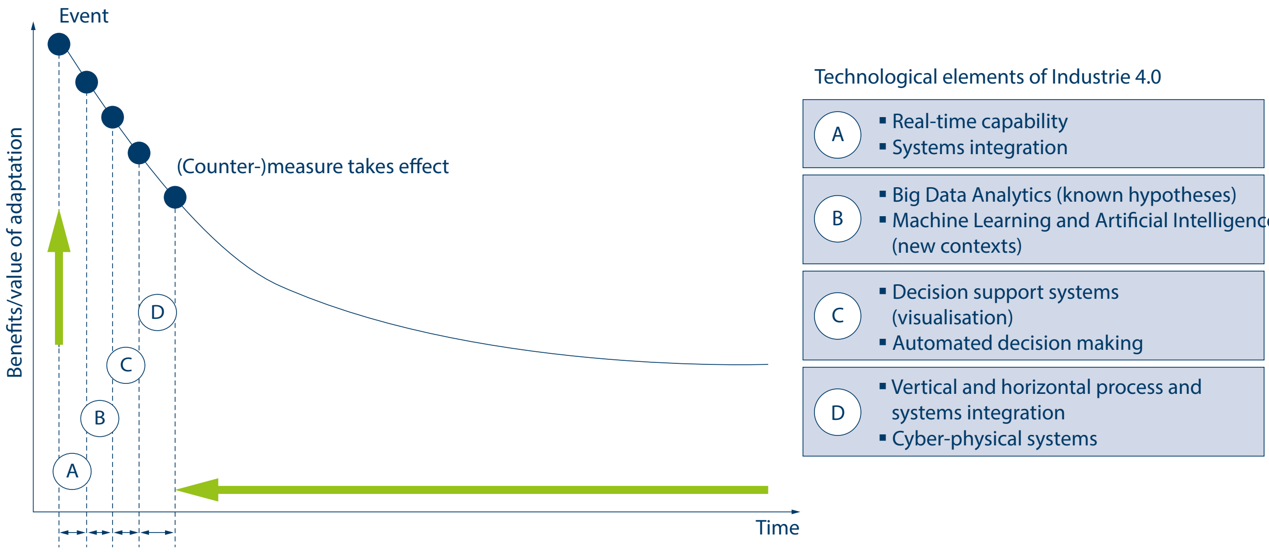


Figure 3: How organisational learning increases the value of an adaptation (source: FIR e. V. at RWTH Aachen University)

2 Objective and methodology

The overall goal of this study is to provide a means of establishing companies' current Industrie 4.0 maturity stage and of identifying concrete measures to help them achieve a higher maturity stage in order to maximise the economic benefits of Industrie 4.0 and digitalisation. The assessment of current processes and the subsequent identification of areas requiring action provide companies with specific and practical guidance for shaping their digital transformation.

2.1 Methodological approach

The close cooperation with the project partners and the practice-oriented methodological approach were based on a combination of workshops and case studies. Case studies investigate a contemporary phenomenon within its real-life context and are used when the boundaries between phenomenon and context are not clearly evident.[3] This methodology was chosen for this acatech study because, from an academic perspective, the field of Industrie 4.0 is a recent phenomenon that lacks clear boundaries, since it is not yet sufficiently standardised and widespread.

Workshops were employed to pool and make use of the different consortium members' experience whilst at the same time encouraging interdisciplinary dialogue and cooperation. This resulted in new cooperation ventures between the participants and allowed projects to be planned and implemented in a short space of time.

Figure 4 illustrates how the study methodology was divided into four constructive stages. Three of these four stages built on each other, while the fourth provided a constant thread throughout the study's duration.

The initial "research and industry consortium" stage formed the basis of the entire study. The extensive support provided by the partners from research and industry over a one-year period allowed a balance to be struck between theory and practice.

The consortium held regular steering committee meetings during which the steering committee members received updates about the project and reviewed its progress.

Finally, the overall methodology was validated in different companies. The validation at technology manufacturer Harting AG & Co. KG is presented in Chapter 6.3. This served to demonstrate that the model developed in the study does in fact cover the relevant areas within a manufacturing company, confirming the validity of its formal aspects and content. The specific recommendations derived from the model were shown to be realistic and to provide companies with practical guidance.

The fourth stage, which ran throughout the project's duration, involved continuous testing of the interim findings. In keeping with the goal of continuous improvement, the findings were directly used to expand and optimise the methodology. This reduced the time and cost involved in the model's development and is reflected in the quality of the methodology.

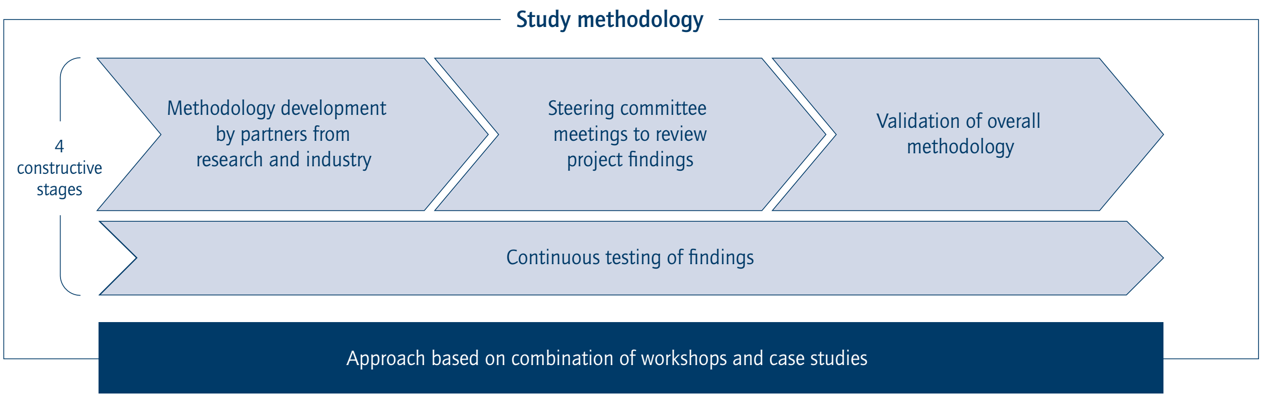


Figure 4: Study methodology (source: authors' own diagram)

3 | See Yin 2009.

The methodology was repeatedly reviewed throughout these stages, and was continuously optimised based on the experience built up over the course of the project. More than ten thousand downloads since its original publication, together with over a hundred academic citations and countless more in industry documents bear witness to the study's extremely positive reception. Project case studies that contributed to a more comprehensive validation of the methodology are included in our companion publication *Using the Industrie 4.0 Maturity Index in industry – current challenges, case studies and trends*.

The study is also inspiring the development of powerful tools. For instance, it provides the basis for the platform operated by the Industrie 4.0 Maturity Center. It is also making an important contribution to the introduction of Industrie 4.0 concepts in specific industries, for example through the Pharma 4.0 initiative of the International Society for Pharmaceutical Engineering (ISPE).[4]

2.2 The acatech Industrie 4.0 Maturity Index

The acatech Industrie 4.0 Maturity Index helps companies to determine which stage they are currently at in their transformation into a learning, agile company. It assesses them from a technological, organisational and cultural perspective, focusing on the business processes of manufacturing companies.

The road towards Industrie 4.0 will be different for every company. It is therefore necessary to begin by analysing each company's current situation and goals. It is important to establish what the company's strategic objectives are for the next few years, the areas in which it intends to add value through Industrie 4.0, the extent to which it hopes to do so, and the indicators that can be used to measure the results. For instance, the goal of boosting a factory's productivity could be achieved either by increasing output or by reducing production costs, while the goal of sustainability could be accomplished through energy efficiency measures and the goal of increased logistics agility by reducing lead times. Once the objectives have been identified, the extent to which Industrie 4.0 is currently deployed in the relevant part of the business can be analysed and measured in order to establish which technologies and systems have already been implemented and how they operate within the company. Based on the results, the next step is to identify the capabilities that the company still needs to acquire in order to successfully implement Industrie 4.0. A gap analysis is used to compare the company's current Industrie 4.0 capabilities with what it requires in order to meet its strategic objectives. The measures needed to acquire the missing capabilities can then be brought together in a digital transformation plan. It is important to recognise that successful transformations happen in stages. Moreover, every company must make a strategic decision about the specific benefits it wishes to achieve. This methodology results in the formulation of a digital roadmap for all the relevant areas, with a step-by-step

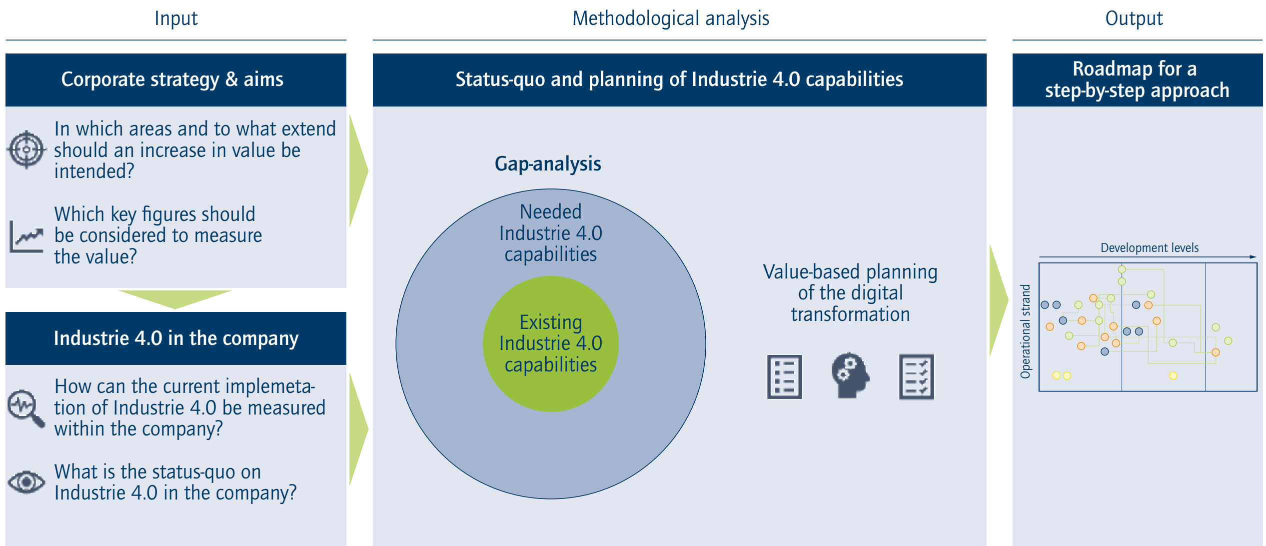


Figure 5: Methodology for introducing Industrie 4.0 (source: authors' own diagram)

4 | See Heesakers et al. 2019.

approach to achieving the benefits that reduces the investment risks for the company. The roadmap helps companies to understand the importance of developing a common digital strategy for the whole business and provides a basis for the step-by-step implementation of Industrie 4.0. This approach is illustrated in Figure 5.

The remaining chapters of this study begin with a detailed description of the acatech Industrie 4.0 Maturity Index's underlying model. The section on structural areas outlines the key organisational capabilities required by an agile company in Industrie 4.0. The following section illustrates potential development goals for current corporate functions in the form of visions. The final part of the study describes the model's application in a manufacturing company and uses a series of real-world examples to further elucidate how the theory works in practice.

3 Design of the acatech Industrie 4.0 Maturity Index

The model's approach is based on a succession of maturity stages, i.e. value-based development levels that help companies navigate their way through every stage in the transformation, from the basic requirements for Industrie 4.0 to full implementation. Since a company's desired target state will depend on its business strategy, it is up to each company to decide which maturity stage represents the best balance between costs, capabilities and benefits for its own individual circumstances, taking account of how these requirements change over time in response to changes in the business environment and the company's strategy. To ensure that all aspects of manufacturing companies are taken into account, the model's structure is based on the "Production and Management Framework".[5] The Framework's four structural areas enable a comprehensive analysis and set out a number of guiding principles that allow companies to identify which Industrie 4.0 capabilities they still need to develop. The Industrie 4.0 Maturity Index provides companies with a valuable tool that can help them to transform their entire organisation.

3.1 Value-based development stages

The introduction of Industrie 4.0 involves significantly upgrading a manufacturing company's digital competencies and capabilities and entails changes across large parts of the organisation. Since this transformation is a highly complex undertaking, it will usually take several years. It should be planned and implemented in such a way as to ensure that positive impacts on profitability – i.e. growth and efficiency – occur at various stages throughout the transformation. Benefits should be made visible at any point in the transformation process in order to support its overall success. This approach enables quick wins while also driving towards the overall transformation goal.

This strategy necessitates a step-by-step approach to the company's development. As part of the study, we developed an Industrie 4.0 development path that starts with the basic requirements for Industrie 4.0 and supports companies throughout their transformation into learning, agile organisations. The path comprises six development stages. Each stage builds on the previous one and describes the capabilities required in order to attain it and the resulting benefits to the company (see Figure 6). It is important that the capability is built step-by-step, i.e. the benefits of the first stage can be achieved with a lower level of capability than stage two. The transformation process is a continuous journey of many successive steps that are taken incrementally and may not be perfectly synchronised across businesses, plants, lines, and cells. It is up to each company to decide which development stage represents the best balance between costs and benefits for its own particular circumstances and should therefore be adopted as the target state for the end of the planned transformation process.

Today, companies are still confronting the challenge of creating the basic conditions for Industrie 4.0. Accordingly, the development path begins with digitalisation. Although digitalisation does not itself form part of Industrie 4.0, computerisation and connectivity are basic requirements for its implementation. These two initial stages are followed by four further stages in which the capabilities required for Industrie 4.0 are developed.

3.1.1 Stage one: Computerisation

The first stage in the development path is computerisation, since this provides the basis for digitalisation. In this stage, different information technologies are used in isolation from each other within the company. Computerisation is already well advanced in most companies and is primarily used to perform repetitive tasks more efficiently. Computerisation delivers important benefits by e.g. enabling cheaper manufacturing to higher standards and with a degree of precision without which it would be impossible to make many modern products. Nevertheless, it is still possible to find many machines without a digital interface. This is especially true of machinery with long cycles or machines that are manually operated. In these cases, terminals are often used to provide the missing link between business applications and machines.

One example for the computerisation stage would be a CNC milling machine. Although it can machine parts with great precision thanks to the use of computer numerical control, the CAD data detailing which actions should be performed still often has to be transferred to the milling machine manually – in other words, the machine is not connected. Another

5 | See Boos et al. 2011, p. 55.

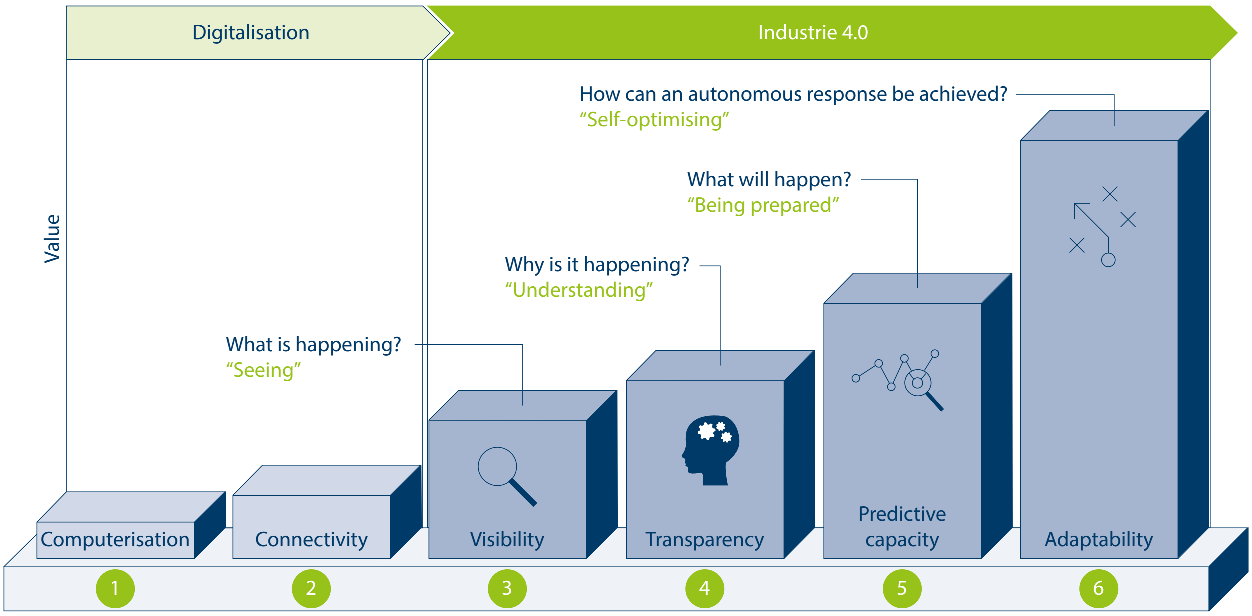


Figure 6: Stages in the Industrie 4.0 development path (source: FIR e. V. at RWTH Aachen University)

example involves business application systems that are not connected to the company's ERP system. This can lead, for instance, to a situation where semi-automated quality assurance is carried out at a test station, but the recorded data is not associated with the corresponding work order. This makes it much harder to subsequently determine which quality issues occurred in which orders.

Companies at this stage typically have a traditional organisational structure geared towards efficient operation of the individual departments. Change and innovation are regarded as a matter for management and are communicated to employees via fixed communication channels.

3.1.2 Stage two: Connectivity

In the connectivity stage, the isolated deployment of information technology is replaced by connected components. Widely used business applications are all connected to each other and mirror the company's core business processes. Parts of the operational technology (OT) systems provide connectivity and interoperability, but full integration of the IT and OT layers has not yet occurred.

The Internet Protocol (IP) is becoming more and more widely used, even on the shop floor. Since the current IPv6 version allows for much longer addresses than its IPv4 predecessor, all the components can now be connected without the need for network address translation. This is a key requirement for the Internet of Things. Connectivity means that, for example, once a design has been created in engineering, its data can be pushed to production, so that the production steps can be executed accordingly (CAD/CAM processes). Once the manufacturing step has been completed, confirmation can be provided automatically and in real time via a Manufacturing Execution System (MES). It also allows machine tool manufacturers to perform remote maintenance on products being used by their customers thanks to the availability of cheap, high-volume data links.

In existing factories, assets are kept in production for as long as they continue to produce quality products. It is not unusual to see machines that are 50 or more years old still in use on the shop floor. Since the Internet Protocol enables standardised communication on the shop floor, new sensor technology mean that these assets, which remain very productive, can easily be connected in order to provide production data.

There is a widespread willingness to embrace change within the company that is supported by continuous development and innovation processes, for example. However, traditional project management methods continue to be employed. This means that although there is a structured approach to change, the process is cumbersome due to the organisation's lack of agility, and it is not easy to make rapid adjustments.

3.1.3 Stage three: Visibility

Sensors enable processes to be captured from beginning to end with large numbers of data points. Falling sensor, microchip and network technology prices mean that events and states can now be recorded in real-time throughout the entire company and beyond rather than just in individual areas like manufacturing cells, as was formerly the case. This makes it possible to keep an up-to-date digital model of factories at all times. We refer to this model as the company's digital shadow. The digital shadow can help to show what is happening in the company at any given moment so that management decisions can be based on real data. It is thus a core building block for the later stages.

Producing a digital shadow is a major challenge for many companies. One problem is that there is usually no single source of truth – data is often held in decentralised silos. Furthermore, for functions such as production, logistics and services it is often still the case that very little data is collected at all, even in centralised processes. In addition the data captured is in many cases only visible to a limited number of people who are able to access and understand the respective domain systems. Wider use of the data is prohibited by system boundaries. In order to achieve the goal of an agile learning enterprise, comprehensive data capture right across the company is essential for the provision of relevant data about the operation throughout the business.

For instance, this makes it possible to more rapidly determine the delivery date variance caused by a particular problem by means of real-time KPIs and dashboards so that production planning can be adjusted by the production manager and customers and suppliers can be kept informed.

This is one area where companies need to change the way they think. Rather than only collecting data to enable a specific analysis or support a dedicated operation, they must instead be able to create an up-to-date model of the entire company at all times that is not tied to individual data analyses. The combination of existing data sources with sensors on the shop floor can deliver significant benefits. Integrating PLM, ERP and MES systems provides a comprehensive picture that creates visibility regarding the status quo. Moreover, modular approaches and apps can help to build the single source of truth.

However, building visibility is not just a technological challenge – it also calls for changes in the company's organisational structure and corporate culture. Collaboration platforms help to strengthen cooperation between different parts of the business. This means breaking down traditional operational structures and involving employees more closely in the change process in order to enable rapid responses to changing customer requirements. It also requires a non-hierarchical communication culture where innovations and changes to established processes can be freely discussed and where the focus is on the desire to improve. Employees are comfortable working with the new level of visibility and are also willing for their own capabilities to be made visible through quality matrixes.

Case study: HIROTEC

Operational downtime is a significant issue facing Original Equipment Manufacturers (OEMs) like HIROTEC AMERICA. The company is a member of the HIROTEC Group, an automation manufacturing equipment and parts supplier with 26 facilities in nine countries around the world. In most cases, the machinery involved runs without condition-based monitoring, essentially operating until a failure occurs. At that time, appropriate personnel are contacted to make the necessary repairs. HIROTEC sought to eliminate this trend of reactive maintenance and lost opportunities by utilising the information and systems it had on hand to gain deeper insight into its operations and processes. Recognising the need for connectivity, data access and scalability, executives at HIROTEC worked to develop a competitive strategy to capitalise on the potential benefits of the Internet of Things (IoT). The initiative began with identifying the fundamental technologies that would fuel the IoT effort. The company opted for an IoT platform in order to enable company-wide device-to-cloud connectivity through one overarching toolset.

Implementing this solution has given HIROTEC increased visibility into its assets and resources by providing greater insight into the assets' current needs and priorities. This has allowed HIROTEC to improve its productivity. "In just six short weeks, we've gained more visibility into our operations than ever before, reinforcing our investment and belief in the power of the IoT", says Justin Hester, Senior Researcher at HIROTEC.

3.1.4 Stage four: Transparency

Stage three involves creating a digital shadow of the company's current situation. The next stage is for the company to understand why something is happening and use this understanding to produce knowledge by means of root cause analyses. In order to identify and interpret interactions in the digital shadow, the captured data must be analysed by applying engineering knowledge. The semantic linking and aggregation of data to create information and the corresponding contextualisation provide the process knowledge required to support complex and rapid decision-making.

New technologies that support the analysis of large volumes of data can be extremely helpful in this regard. Big data is a buzzword that is frequently mentioned in this context. It is used to describe mass data that can no longer be processed and analysed using conventional business analytics processes. The term big data also encompasses the technologies and applications that enable these extremely large and often heterogeneous data sets to be processed and combined.

As a rule, big data applications are deployed in parallel to business application systems such as ERP or MES systems. Big data applications thus provide a common platform that can be used e.g. to carry out extensive stochastic data analysis in order to reveal interactions in the company's digital shadow.

This transparency regarding the relevant interactions can, for example, be used to carry out condition monitoring of machinery and equipment. Recorded parameters are searched for mutual events and dependencies that are then aggregated to produce complex events reflecting the condition of the machine or equipment. Among other things, transparency is therefore a requirement for predictive maintenance.

The benefits of employing big data are not solely dependent on the technological aspects – they also require a willingness to use data in decision-making processes across every level of the company hierarchy. Employees initiate changes and innovations and are involved in their implementation, and this results in collaboration between experts from different departments. The use of agile management techniques for change processes means that the benefits start to appear within a short timeframe.

3.1.5 Stage five: Predictive capacity

Building on the transparency stage, the next development stage is predictive capacity. Once it has reached this stage, the company is able to simulate different future scenarios and identify the most likely ones. This involves projecting the digital shadow into the future in order to depict a variety of scenarios that can then be assessed in terms of how likely they are to occur. As a result, companies are able to anticipate future developments so that they can take decisions and implement the appropriate measures in good time. While measures still have to be carried out manually, longer lead times help to limit negative impacts. Reducing the number of unexpected events caused e.g. by disruptions or planning variance enables more robust operation of the business. It makes it possible, for example, to flag up recurring logistics issues such as carrier failure before they even occur so that they can be prevented, in this instance by changing carriers.

A company's predictive capacity is heavily dependent on the groundwork that it has previously undertaken. A properly constructed digital shadow combined with a knowledge of the relevant interactions will help to ensure that both the forecasts and the recommendations based on them are of a high standard.

Once companies are able to anticipate future events, they must also be prepared to take any measures required to minimise the potential negative impacts of these events. This will entail organisational and cultural changes within the company. Employees will need to be given adjusted decision-making powers to enable rapid decision-making as and when necessary. The organisational structure will need to be modified so that capacity can be swiftly adjusted to new situations. Predictive capacity also calls for critical reflection and openness to change.

3.1.6 Stage six: Adaptability

Predictive capacity is a fundamental requirement for automated actions and automated decision making. Continuous adaptation allows a company to delegate certain decisions to IT systems so that it can adapt to a changing business environment as quickly as possible.

The degree of adaptability depends on the complexity of the decisions and the cost-benefit ratio. It is often best only to automate individual processes. Accordingly, the fundamental feasibility of performing repeatable operations autonomously should be investigated. It is, however, important to carefully assess the risks of automating approvals and acknowledgements for customers and suppliers. Examples include changing the sequence of planned orders because of expected machine failures or to avoid delivery delays.

The goal of adaptability has been achieved when a company is able to use the data from the digital shadow to make decisions that have the best possible results in the shortest possible time and to implement the corresponding measures automatically, i.e. without human assistance.

Adaptability also places a number of demands on the company itself. It calls for dynamic collaboration across the value network in order to continuously review both existing skills and the development of core competencies, so that they can be adjusted as necessary. Change is regarded as the norm. Flexible communities and agile project management create an organic organisation. The adoption of a knowledge-based approach requires the continuous accumulation of knowledge and lifelong learning for employees.

3.2 General model design

This chapter describes the general design of the model underpinning the acatech Industrie 4.0 Maturity Index (see Figure 7). To ensure that the model provides a full description of a manufacturing company, the acatech Industrie 4.0 Maturity Index is based on the "Production and Management Framework".[6] The framework divides the internal aspects of a company into corporate structure, corporate processes and corporate development.[7] Corporate structure refers to those aspects of a company that are indispensable for the production of its goods and services. Corporate processes, on the other hand, refer to the process chains in every area of the company, while corporate development refers to the strategic and operational development of the company.[8] Corporate development encompasses strategy, optimisation, operations and realignment. It thus includes all the activities involved in strategic and operational management.[9] The function of corporate development is to successfully maintain the level of performance that the company has already attained (operations), continuously improve this performance (optimisation) and, if necessary, radically realign it (realignment). The digital transformation roadmaps drawn up on the basis of the Industrie 4.0 Maturity Index are implemented in the organisation through the corporate development process in order to facilitate this optimisation and realignment.

The acatech Industrie 4.0 Maturity Index breaks a company's structure down into the four **structural areas** of resources, information systems, culture and organisational structure. A detailed description of the four structural areas is provided in Chapter 4. Two guiding **principles** together with the necessary **capabilities** are identified for each structural area. The capabilities are geared towards attainment of the various development stages and provide manufacturing companies with the basis for transforming themselves into agile organisations.

Corporate processes form the basis of the five **functional areas** investigated by the Index. The five functional areas of development, production, logistics, services and marketing & sales are addressed in Chapter 5. A vision is outlined for each functional area, illustrating the features that characterise learning, agile companies.

The application of the acatech Industrie 4.0 Maturity Index is described in Chapter 6. In use, the structural areas, functional areas and maturity stages are combined in order to determine a manufacturing company's overall maturity and the maturity of individual functional areas. We show how once a company has established its current maturity stage it can develop a digital roadmap containing specific measures in an established sequence for both the functional and structural areas.

6 | See Boos et al. 2011, p. 55.

7 | In addition to the internal aspects of the company, the "Production and Management Framework" also addresses stakeholder groups and environment spheres. However, these fall outside the scope of the acatech Industrie 4.0 Maturity Index and are therefore not included in our study.

8 | See Boos et al. 2011.

9 | Ibid, p. 55.

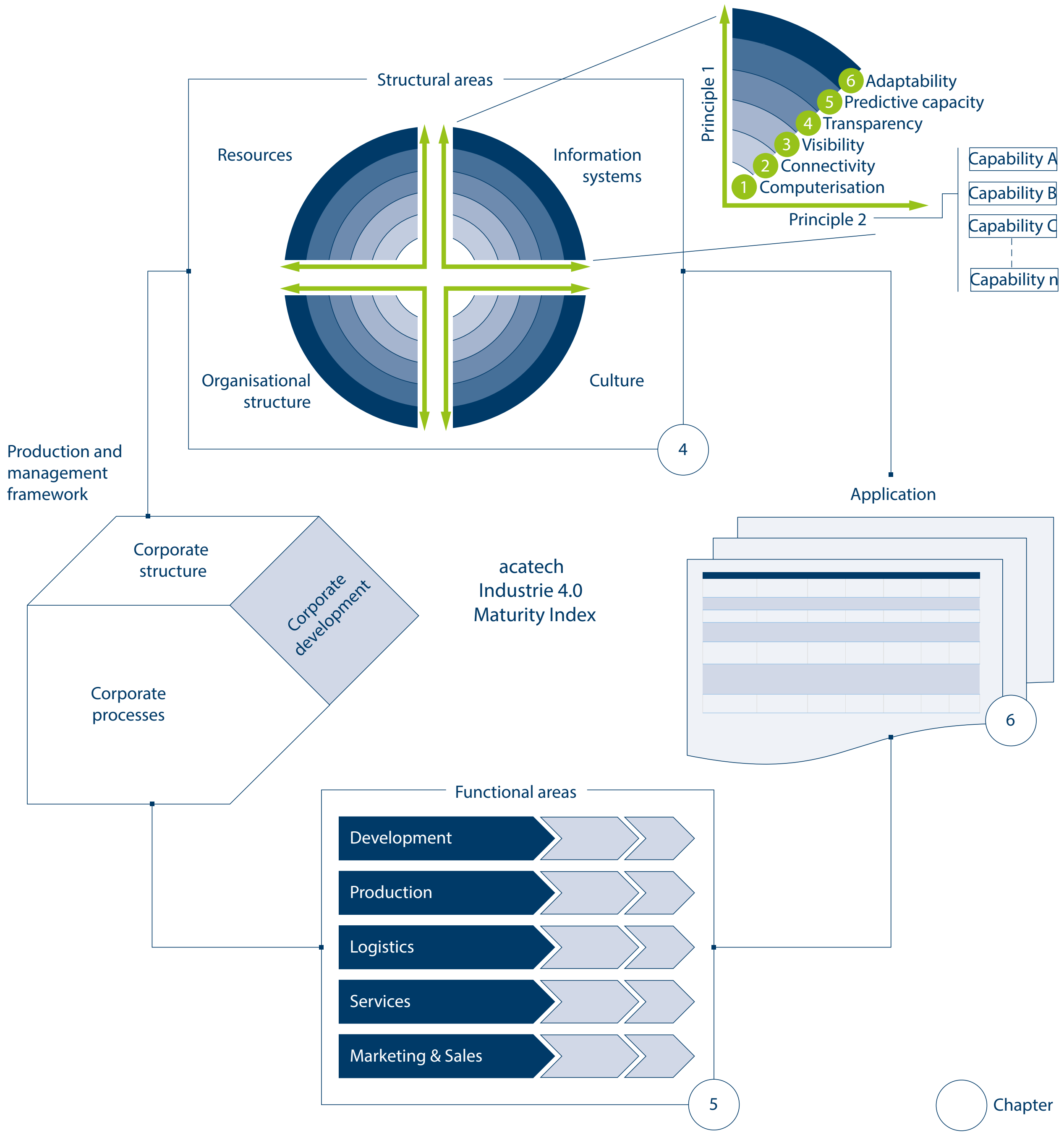


Figure 7: Model design of the acatech Industrie 4.0 Maturity Index (source: authors' own diagram)

4 Industrie 4.0 capabilities for businesses

This chapter describes the capabilities that a manufacturing company must possess in order to transform itself into a learning, agile organisation. It considers the four structural areas of resources, information systems, culture and organisational structure (see Figure 8). Together, these structural areas make up the organisation's structure. They are connected by the six stages of the Industrie 4.0 development path which are depicted as six concentric circles.

Each structural area has two principles running across it that serve as a guide for its continued development. Each principle comprises a number of capabilities that must be successively developed for each value-based development stage. The extent to which these capabilities are implemented determines the maturity stage of the relevant principle. The maturity stages of both principles are combined to provide an overall assessment of the structural area's current development stage. In Figure 8 the assessments of the structural areas are depicted by the four green dots.

4.1 Resources

In the acatech Industrie 4.0 Maturity Index, "resources" refer first to tangible, physical resources. These include a company's workforce (human resources), machinery and equipment, tools, materials and the final product. The workforce must possess certain competencies in order to make the most of the captured information. Complementary, correctly configured technical resources can help to reduce both data and action latency (see Introduction). In addition to fulfilling their particular function, companies should try to ensure that their resources have an interface between the physical and digital worlds. This creates an information viewpoint in the digital world (the digital shadow) that facilitates the learning process required to increase the company's agility. Two principles follow from this:

Firstly, the resources must possess the necessary capabilities to work in an information-based manner.[10] Employees should therefore be able to identify data sources and potential processing techniques. As far as the technical resources are concerned, technological features must be implemented to enable data collection and to process this data into information. In this context, information refers to data that is interpreted in order to support decision-making. The resulting principle of **digital capability** facilitates an information-driven way of working that creates an awareness of the real situation on the ground. Rather than being based on the targets in a plan – which are often derived from assumptions or forecasts – this approach relies on feedback from

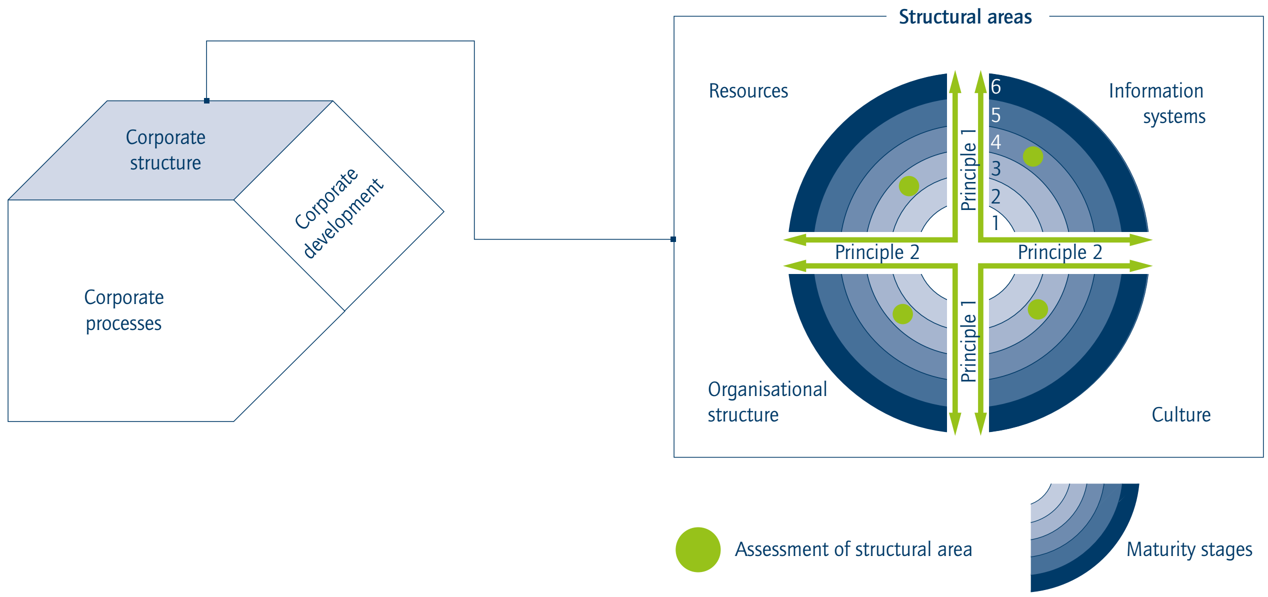


Figure 8: Structural areas (source: authors' own diagram)

10 | In this context, information refers to data that is interpreted in order to support decision-making.

the process environment. However, it is still up to the workforce to ensure that the system is properly configured so that this way of working can fulfil its potential.

Secondly, a clear overall picture only emerges once different pieces of information are combined. To make sure that the information is of sufficient quality, data should be exchanged and if possible generated in as structured a manner as possible. This requires the appropriate interfaces, as well as a consensus regarding the purpose of the communication. Accordingly, the principle of **structured communication** describes the technical approach to communication media for employees and the interfaces between both people and machines and between different machines. Figure 9 provides an overview of the principles and associated capabilities. These are explained in detail below.

4.1.1 Digital capability

In order to generate and analyse data and implement the corresponding decisions, the existing resources – i.e. all personnel, machinery and equipment, tools, materials and products – must acquire certain competencies or be upgraded with the relevant technological components. These basic requirements for information-based working and learning are collectively referred to in the model as "digital capability".

Provide digital competencies

Because of the increasingly widespread use of information and communication technology in products and processes, it is important for companies to promote an interdisciplinary approach in the way their employees think and act. Employees should be more closely involved in innovation processes so that these can benefit from the widest possible range of knowledge. The ongoing automation of many process steps means that, in the future, employees will need to be capable of performing high value-added work[11] – in the long-term, applied skills will no longer be enough on their own. It will also be necessary to give employees more individual responsibility in order to speed up the learning and decision-making processes.[12]

When employees have to make a decision, it is more important than ever that they should be able to access, gather and process data and information so that they can come to a robust final decision. As well as a basic grasp of the value of information in short-, medium- and long-term decision-making, the workforce should also possess a common understanding of Industrie 4.0. As information systems and communication technologies become increasingly widespread, companies must also help their employees to acquire integrated, interdisciplinary IT skills that provide them with a basic understanding of the applications and processes used in different parts of the business, thereby upgrading long-established occupational profiles.[13]

When employees are working with IT systems on a regular basis and thus often coming into contact with sensitive data, it is essential for them to be aware of the importance of IT security. It is a crucial part of employee training to create awareness of possible data leaks and the reasons for them. Given the growing popularity of social media and collaborative tools, new rules must be developed and applied to internal and especially external communication. While having access to a wide data base is useful when making decisions, part of this data may form the intellectual property of the company and should not be shared with third parties. Standards like IEC 62443 provide a comprehensive

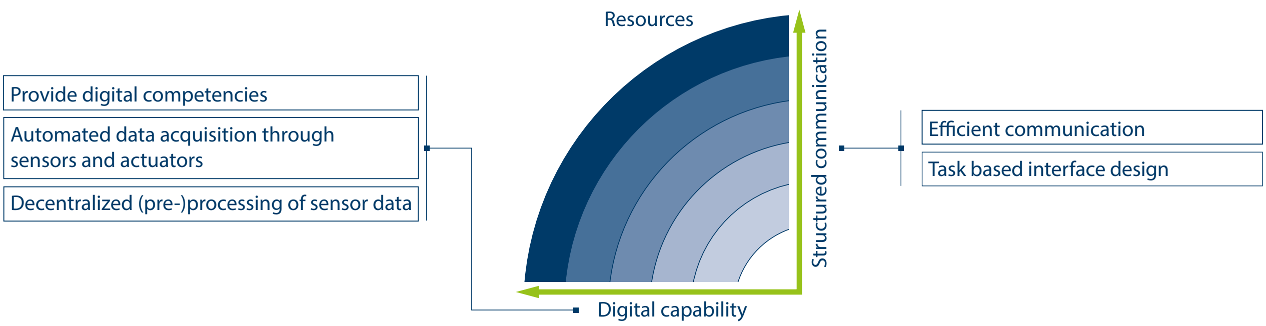


Figure 9: Capabilities of the structural area "resources" (source: authors' own diagram)

11 | See Kagermann/Nonaka 2019.
12 | See acatech 2016.
13 | Ibid.

security strategy for the IT security of networks and manufacturing systems.[14]

Data acquisition through sensors and actuators

As far as the technological resources of machinery and equipment, tools and products are concerned, the priority is their development to create cyber-physical systems (CPS). CPS are created by enhancing mechatronic components with embedded systems such as sensors, actuators and information processing systems, together with a communication layer.[15] Experience indicates that companies attempting to implement CPS tend either to build local control loops that do not interact with other resources or to use labels (barcodes or RFID) to inventory existing objects without making full use of the potential of automatic identification.[16]

It is already common for machinery and equipment in particular to be fitted with numerous sensors. These are mostly used to monitor the stability of technical processes and any short-term adjustments made to them. In addition to this standard monitoring of physical parameters, a key requirement for monitoring business processes through the generation of feedback data is the ability to locate objects. Furthermore, advances in imaging are opening up new ways of recording quality data. Defining the relevant data requirements and selecting the right sensors are therefore key to the creation of a digital shadow.

Decentralised (pre-)processing of sensor data

Alongside sensors and actuators, embedded systems are also key components of cyber-physical systems. They form the link between the communication layer and the electromechanical components (actuators). Increases in processing power and reductions in transistor size are making it possible to build ever smaller and cheaper units. This allows (pre-)processing to be decentralised and performed directly on embedded systems linked to the technical resources. The reduction in the signal propagation delay means that time-critical computations can be carried out faster, enabling new applications, for example in the field of human-machine collaboration. Embedded systems can be deployed in a variety of different ways – while it is already common for machinery and equipment to have their own on-board processors, the relevant technologies are also increasingly being incorporated into tools and transport equipment.

4.1.2 Structured communication

The suitability of centralised control systems is increasingly being called into question as the required number of decisions rises. Growing complexity means that centralised systems are becoming harder to manage. Consequently, decentralised control loops, which have already been used to optimise many technical processes, are also set to become established at the business process level. The introduction of these control loops can have a positive impact on the responsiveness and robustness of business processes. However, in order to ensure delivery of the relevant goals, all the stakeholders must work together to align the target systems.[17] The use of communication technology to create temporary networks enabling the resources to interact with each other is therefore a key requirement.

Efficient communication

Communication between employees should always be traceably documented, redundancy-free and enabled in a manner that meets the needs of the relevant stakeholder groups. Employees still spend a lot of their time searching and waiting for information. Traceable communication means that the context of the message is known thanks to automated tagging or can be accessed in real time by integration with the relevant business application system. Redundancy can be prevented through centralised data storage. If there is only one valid version of a file (single source of truth), then instead of the file being sent to a recipient they are simply provided with the relevant authorisation to access it. Moreover, role profiles and credentials make it possible to add employees to a communication process contextually and, if necessary, retroactively. Similar requirements apply to approval procedures. Even today, analogue signatures are often required to authorise certain decisions. The introduction of digital signatures makes approval procedures faster and more transparent and even enables approvals to be revoked. The stakeholders are directly informed of the status and the relevant

Capabilities

14 | See IEC 62443.

15 | See Bauernhansel et al. 2016.

16 | For example, a company in the metalworking industry ran a pilot test that involved fitting an old machine with structure-borne sound sensors in order to monitor wear and tear on the tool so that preventive maintenance could be carried out. Measurements were recorded and analysed and a correlation was eventually identified between structure-borne sound and remaining service life. However, since the solution was developed as a closed control loop and was not integrated with the company network, maintenance jobs still have to be created manually.
In another pilot project, a range of tools for a particular type of machine that had previously been labelled by hand were given RFID labels so that they could be located more easily. Each geoposition was associated with a particular status (in use, in storage, being reworked). However, this information was not entered into the company's Manufacturing Execution System (MES).

17 | See Bauernhansel et al. 2016.

information can be directly linked to the approval procedure. IT systems that support this type of communication are collectively known as groupware.

Task-based interface design

In human-machine communication, identification and visualisation technologies form the main interface between the real world and the digital world. Assistance systems are becoming essential due to the growing complexity of processes and the increasing range of tasks that employees are expected to perform. Auto-ID solutions enable direct recognition of objects and their attributes. In conjunction with a graphic interface, this makes it possible to provide context-sensitive information.

Hardware interfaces play a key role in enabling different types of technological resources to interact with each other. In the future, cyber-physical systems will not necessarily exchange self-descriptions across different levels of the automation pyramid but will instead do so as part of a dynamic network.[18] Identification technologies enable (mutual) recognition of technological resources and people and the negotiation of specific information requirements. When acquiring new systems, it is important to take the connectivity of their control systems and sensors into account. These may be implemented as wireless or wired solutions, depending on the conditions in which they are deployed. Preference should be given to open interfaces in order to avoid dependency on particular machine or tool manufacturers. In addition, the appropriate (e.g. industrial ethernet-based) infrastructure should be installed in the factory. As for legacy systems, a growing number of retrofit solutions are becoming available for existing machines, meaning that these too can be integrated.[19] As well as enabling connectivity between in-house systems, these solutions should also provide internet connectivity. This is especially important so that the maintenance and production planning functions can remotely access machinery and equipment.

The same thing applies to materials – if there are enough reporting points, it is possible to track and trace goods if they can be automatically identified either via their carrying medium or via identifiers on the goods themselves. In conjunction with systems integration (see information systems), this makes it possible to meet customers' growing requirements with regard to product traceability.

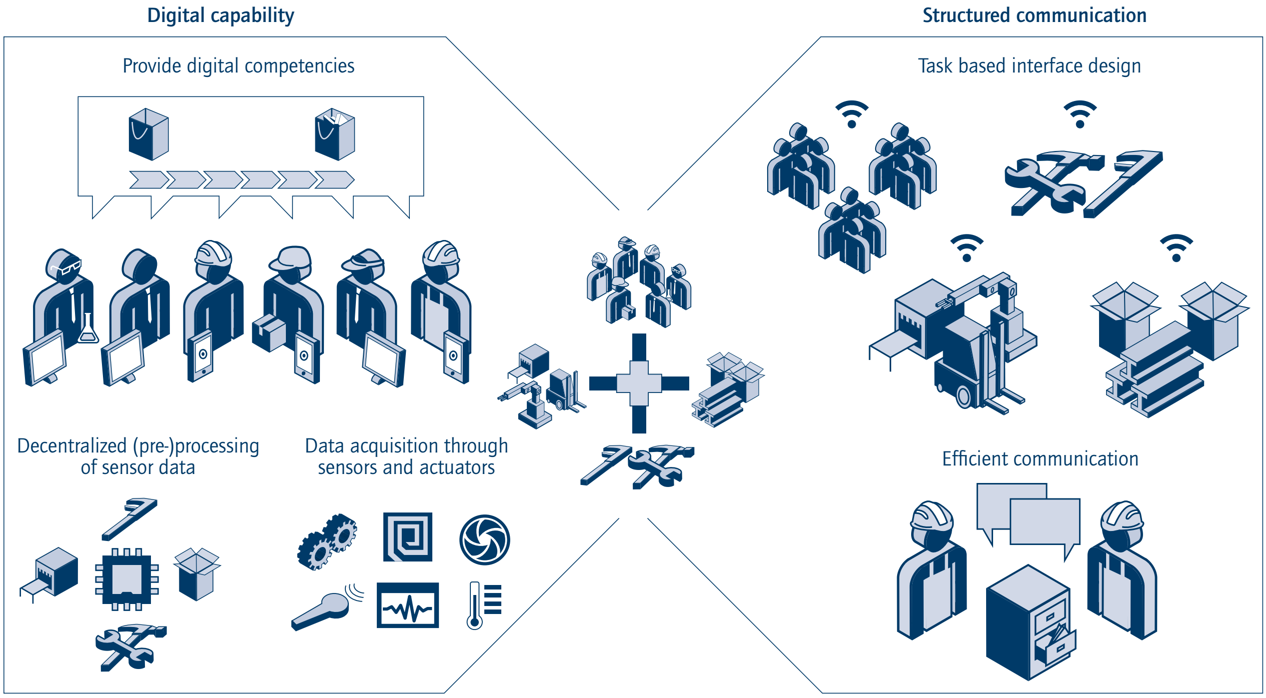


Figure 10: Capabilities required in the structural area "resources" (source: authors' own diagram)

18 | See Bauernhansel et al. 2016.
19 | See Ciupek 2016.

A critical factor in all these developments is the company's ability to identify its information requirements and select the appropriate technologies. When carrying out process integration, it is also important to take usability and ergonomic aspects into account. For the human-machine interface, see Chapter 4.2.1.

4.1.3 Conclusion

Figure 10 illustrates the characteristics that a manufacturing company's resources should possess once it has reached the "adaptability" maturity stage. Established employee skills profiles should have been expanded to include broad-based IT skills. Technological resources should have had a data processing layer added to them in order to control the connected sensors and actuators and generate feedback data. The resources interact to aggregate this data and create a digital shadow. Human-human, machine-machine and human-machine communication should be configured so that data and information can be exchanged in real-time and so that all the stakeholder groups are included in the communication process.

4.2 Information systems

Information systems[20] are socio-technical systems in which information is provided based on economic criteria by both people and information and communication technology. They prepare, process, store and transfer data and information. The configuration of a company's information systems is key to ensuring that the available data and information can be used to make decisions. The progress that has been made with regard to the digitalisation of businesses means that it is becoming easier and easier for manufacturing companies to make these data-based decisions in real-time with the aid of a digital shadow. However, many manufacturers are still failing to use this data and information to support their decision-makers. There are two reasons for this:

Firstly, the captured data is not processed into information and, because it is not delivered in a suitable form, employees cannot use it to support their work. So how can the captured data be prepared and delivered to employees in a way that allows them to make data-based decisions? In order to be usable for decision-making, as well as being analysed and processed into information, the data must also be delivered in a user-friendly manner. Consequently, the first principle of information systems is that **data should be prepared and processed in a manner that supports decision-making**. In order for the data to be usable, the organisation must meet the technical requirements for real-time access and possess an infrastructure that enables the necessary data processing and seamless information delivery.

Secondly, the same, centralised data is not used throughout the different parts of the company. Systems must therefore be integrated in order to enable the use of common data across the value chain. To do this, it is necessary to create an information system architecture for agile companies with a central platform that connects existing IT systems to each other and to the resources. This ensures that everyone is using the same data – rather than data having to be duplicated in different IT systems, it is all contained in a single, primary information system (single source of truth). Consequently, the second principle is: **integration in order to enhance data use and increase agility**. The creation of a platform connecting the different information systems requires standard interfaces, flexibility, openness, comprehensive IT security and appropriate data quality.

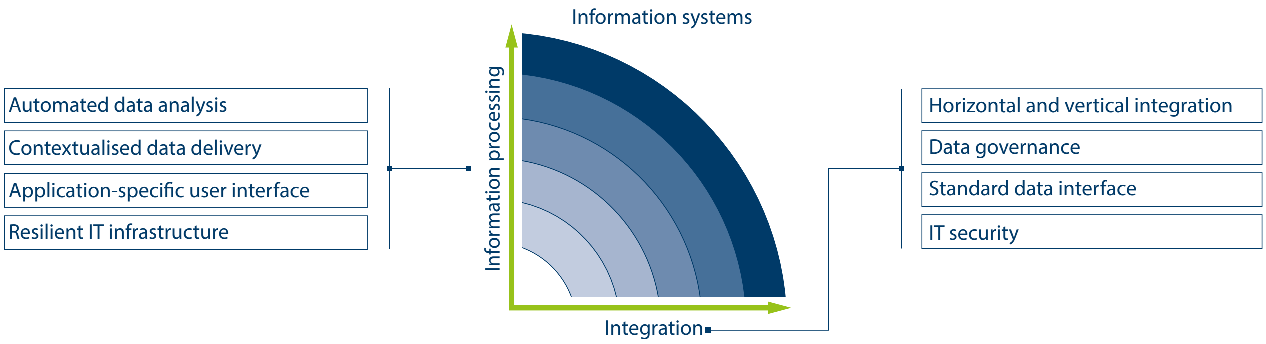


Figure 11: Capabilities of the structural area "information systems" (source: authors' own diagram)

20 | This study draws a distinction between information systems and IT systems. The term "IT systems" describes individual application systems (e.g. ERP systems), whereas "information systems" refers to socio-technical systems as defined above.

Capabilities

Figure 11 illustrates the development of information systems using the principles of information processing and integration.

4.2.1 Self-learning information processing

The principle of information processing involves aggregating data in order to create information and provide material to support decision-making so that decisions are ultimately data-based. It requires companies to understand data and information as a resource that adds value, as well as to process this data and information and make it available to their employees.

In this context, self-learning refers to the use by information systems of new technological solutions capable of identifying cause-and-effect relationships in order to continuously improve their computational processes. This is enabled by technologies such as artificial intelligence and machine learning.

Automated data analysis

Data-based decision-making is enabled by automated data analysis that continuously aggregates the data to produce information, extracts knowledge from this information and provides the user with information to support their decisions. This requires automatic data analysis capabilities that allow cause-and-effect relationships to be identified using data from different sources and future events to be predicted using e.g. simulations or regressions. The data streams must be continuously monitored in real time according to specific rules and correlations so that they can be aggregated to produce value-added information. One simple application is the continuous analysis of various machine and tool parameters, allowing e.g. machine faults or quality issues to be predicted with a high degree of confidence. This is often referred to as "condition monitoring".

In agile companies, data-based decisions are also taken at the overall production level. One example of such a decision would be to ascertain how on-time delivery would be impacted by prioritising specific orders or temporarily shutting down a machine for maintenance. In other words, as well as being necessary at the machinery and tools level, automated data analysis is also required at the overall production level. Since the relevant data streams are much larger, broader and more diverse, data analysis at this level involves the processing and correlation of very large and frequently heterogeneous data sets. Accordingly, companies will need applications and technologies capable of performing this type of processing.

It is also important that the data analysis should not be confined to known cause-and-effect relationships – companies must keep learning and identifying new patterns in the data that they capture. When unforeseen events occur such as machinery breakdowns or delivery deadlines being missed, the causes should be analysed and interpreted on the basis of the relevant data. Once a validated correlation has been identified, it can serve as a new pattern for future use.

Recurring events can be used to generate assumptions about how the data will develop in the future. Optimisation algorithms integrate the impacts of e.g. a predicted breakdown (for instance delays to delivery deadlines) and automatically generate corresponding recommendations.

Deliver contextualised information

Contextualised information delivery allows the results of the data analysis to be used to support decision-making. It means that instead of the user having to search for the information across several different IT systems and process, sort or interpret it themselves, the information is prepared and delivered in accordance with the requirements of the specific context (push principle). Successful companies apply the "system of engagement" principle, which means that employees are informed by efficient and effective information logistics that deliver the right information to the right place, at the right time, in the right quality, to the right person and in the right quantity. For instance, it is possible to provide an easily understood visualisation of complex assembly operations using context-based 3D animations. Other examples of information delivery include providing the production control department with projected order completion dates or maintenance workers with details of the cause of a breakdown together with additional in-depth information.

Apps can be used to ensure that only the relevant information is delivered (see Figure 12). The app obtains the required information from the underlying IT systems so that the employee is only provided with the information required to perform the task at hand.

Task-specific user interfaces

The information provided must be continuously matched to the needs of the recipient and its format adapted to its current use. Its content and presentation should be adapted to the task being performed and the employee's skill level. Depending on the application, user interfaces may, for instance, deliver data in the form of tables, animations, Augmented Reality or speech. In

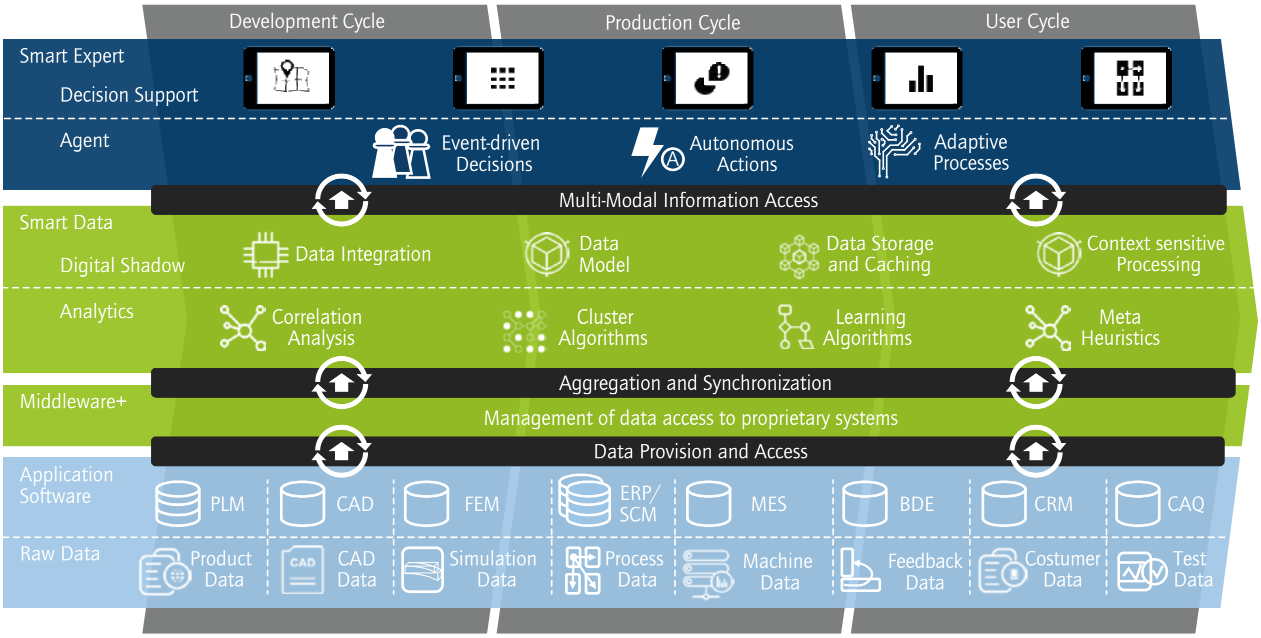


Figure 12: Infrastructure of the Internet of Production (source: Schuh et al. 2017)

other words, as well as having the data displayed to them, employees may also be provided with verbal instructions to guide them through the process. Users have intuitive options for responding to events and communicating with the IT systems. Gesture or voice control may be used, depending on the task in question.

Build a resilient IT infrastructure and implement situation-based data storage

Data analysis and delivery rely on a resilient IT infrastructure that fulfils the relevant technical data capture, transfer, storage and processing requirements and guarantees IT systems functionality. This requires the IT infrastructure's technical performance to be continuously adapted to current requirements and is enabled by redundant data storage or system design. Depending on the design, these redundancies may be implemented internally or in the cloud. Backups or specialised software prevent threats to people and material assets and guarantee the system's long-term usability. Situation-based data storage ensures that the data can be accessed within an appropriate timeframe. In-memory databases allow frequent accessing of the data, so that it can be used to provide rapid and stable decision-making support.

The Internet of Production refers to the architecture of information systems that can provide real-time information in a systematic, situation-based manner (see Figure 12). Raw data obtained from specific systems such as Manufacturing Execution Systems (MES) or Enterprise Resource Planning (ERP) systems can be made available to specific users in a targeted manner via middleware. The data systems for handling the large volumes of data needed to create the digital shadow and the technology for carrying out the in-depth data analysis are located in the next layer up. The data can ultimately be used to support decision-making or as the basis for decisions taken autonomously by agents.

4.2.2 Information system integration

Integrated information systems are intended to ensure the use of common data throughout the value chain. The goal of the integration principle is to integrate existing IT systems in order to facilitate access to and use of the data and information that they contain.

Integrate information systems vertically and horizontally

The use of common data throughout the value chain is enabled by information systems that are fully integrated both vertically and horizontally. Information is exchanged continuously between all the IT systems in the value chain so that order information is always linked to product, work and process instructions and customer information, and all users access the same data set. This marks a move away from the status quo of overly complex architectures with redundant data storage. The primary IT system containing the order information is linked to everything from the production and planning systems to the machine and field level. Once they have completed a job, the machines automatically send back an order status report.

This creates a "single source of truth" – information only resides in one primary logical information system that is accessed by all the users in the value chain and the system of record. Today, product and design data is often found in a PLM system, whilst order data resides in the ERP system and the associated customer data is located in the CRM system. The absence of metadata integration means that the development, production and marketing functions thus have their own, separate data sets which are not shared effectively across the related operations applications and decision support tools. As a result, changes in one of these functions are not shared with the others. Agile companies therefore require a logical or physical platform that integrates and provides users with the information they need for operations and decision-making and enables access to data and information. It is also important to ensure transparency regarding the IT systems that are employed – different departments must not be allowed to use their own shadow IT systems that are not overseen by the IT department.

Standardise data interfaces

Rather than requiring everything to be stored centrally, the key to creating a single source of truth is to connect all the IT systems to each other via standard data interfaces. APIs, micro services and data interfaces facilitate the exchange of data and information from individual IT systems and should therefore be selected based on the required information flow. To always ensure an agile information flow and data exchange transition when switching from one information system to another, it is necessary to implement neutral or standard interfaces and data exchange formats across all the relevant systems.[21] These should use an open standard that is universal for the application category in question. One example of a standard interface that is particularly popular in the field of Industrie 4.0 is the OPC-UA[22] architecture for machine-to-machine interfaces.

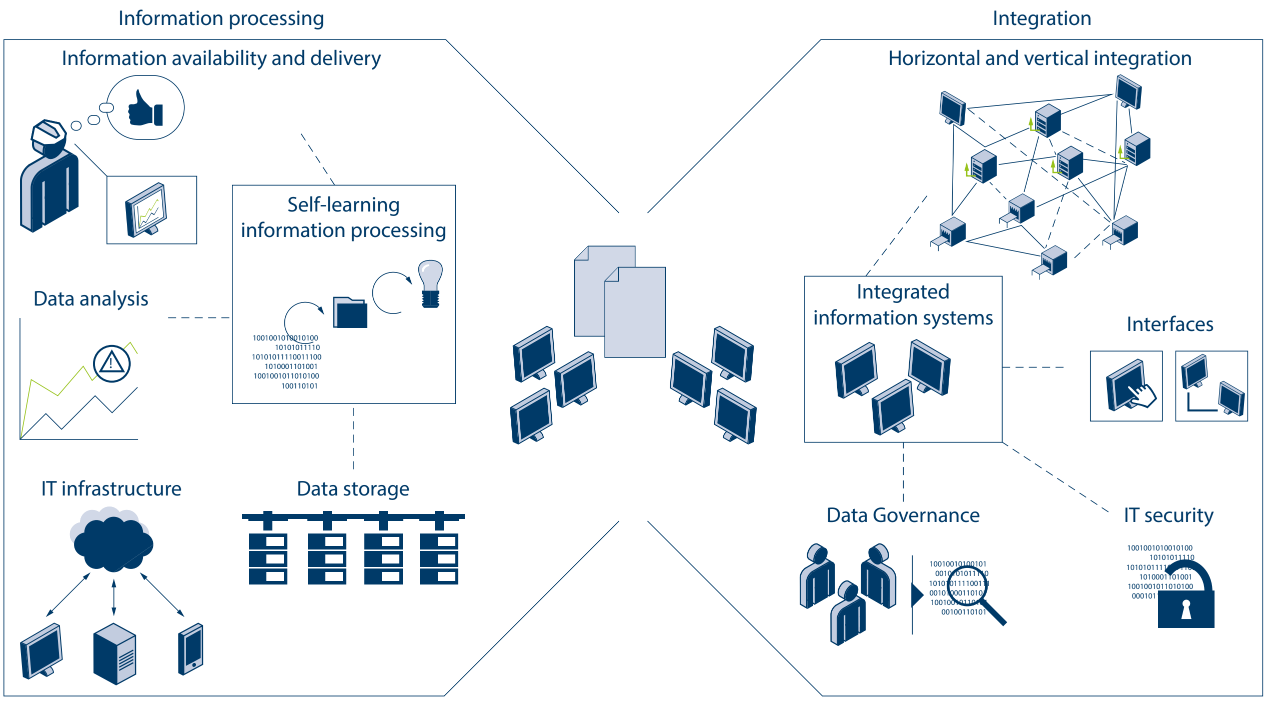


Figure 13: Capabilities required in the structural area "information systems" (source: authors' own diagram)

21 | See Schuh et al. 2014, p. 288ff.

22 | The OPC Unified Architecture (OPC UA) is a platform-independent communication protocol for machine-to-machine communication.

Implement data governance

In addition to the data interfaces, IT systems integration also relies on sufficiently high data quality. Poor data quality in the IT systems results in incorrect aggregated data and inaccurate feedback, ultimately undermining confidence in both the IT systems and their contents. This makes it impossible to achieve the goal of data-based decision-making. Companies must therefore acquire the relevant technical and in particular organisational capabilities in order to improve the quality of the data. Data governance policies provide organisations with guidance for the processing, storage, management and presentation of high-quality data within the company. Technical capabilities for improving data quality include automated data cleansing (identification, standardisation, duplicate removal, consolidation and enhancement of data) and master data management systems.

Upgrade IT security

The increasing integration of information systems as well as human factors and other contributors is accompanied by the risk of criminal attacks. The potential damage that these attacks can cause increases in proportion to the degree of integration. IT security encompasses different strategies for identifying and implementing security measures. Compliance with standards such as IEC 62443 can help to contain the risks. Such standards include proactive measures to maintain IT security and adapt it in response to changing circumstances. The measures cover asset administration issues, user identification and authentication, system health validation and data flow control. Responses to existing IT security incidents are also covered in IT security standards.

4.2.3 Conclusion

Figure 13 illustrates the characteristics that a manufacturing company's information systems should possess once it has reached the 6th maturity stage of "adaptability". High-quality data are stored centrally and analysed automatically. The analysis and processing are self-learning, meaning that the information systems continuously adapt to changing circumstances. The knowledge acquired in this way is delivered to employees in a contextualised manner and supports them in their work. This is made possible thanks to integrated information systems. Horizontal and vertical integration and standard interfaces combine to create highly flexible information systems.

4.3 Organisational structure

Whilst the transformation into a learning, agile company is enabled by the technologies described above, its implementation requires the right organisational structure. In our model, organisational structure refers to both a company's internal organisation (structure and operational processes) and its position within the value network. In contrast to area of "culture" (see below), the "organisational structure" establishes mandatory rules that organise collaboration both within the company and externally. "Culture" covers the value system within the company and thus describes the soft factors of collaboration. Nevertheless, both structural areas are mutually dependent and must be coherent with each other.

The structural area "organisational structure" is spanned by the two principles of **organic internal organisation** and **dynamic collaboration** within the value network. It therefore describes the organisation from both an internal and an external perspective (see Figure 14).

4.3.1 Organic internal organisation

The organic organisation is the antithesis of the mechanistic organisation. Its employees have fewer constraints and a high degree of individual responsibility. This form of organisation is thus particularly well suited to organisations with highly skilled workforces that exist in a dynamic environment.[23]

Flexible communities

In an agile organisation, the necessary resources within the company must be configured dynamically. In terms of the company's organisational structure, this means that employees will regularly be required to change the tasks they perform and switch to different teams. Even though they will continue to be assigned to a particular department in the company's organisational chart, in practice they will perform their work as members of task- or goal-oriented teams. At the same time, the company needs to facilitate collaboration between experts on specific topics by creating parallel teams of experts to address specialised themes. This approach aims to enhance communication between different departments and pool employees' skills. It allows the company to ensure that people with different skills from different parts of the business are all pulling in the same direction in pursuit of a common goal. The way the company is organised should therefore enable increasingly needs-based cooperation in individual teams.[24]

23 | See Burns/Stalker 2001.

24 | See Jassawalla/Sashittal 1999; Love/Roper 2004.

This approach ultimately leads to the concept of communities, where organisational units form around a specific theme (e.g. the implementation of a new IT solution) or task (e.g. operating milling machines). While permanent communities may take care of the company's routine business, other communities may be project-based and be formed on a purely temporary basis before being disbanded again. The goal of this form of organisation is to ensure that work is performed by the employees with the right skills for the job, irrespective of where they sit in the hierarchy or which department they belong to. It also enables a rapid response to new events and knowledge. In companies such as Google, for instance, it is not unusual for small teams to form spontaneously around a particular topic and build a prototype within a few days or weeks which is then evaluated to decide whether it should be taken any further.

This form of organisation is subject to certain restrictions. Evidently, the efficient completion of routine operations should not suffer as a result of this concept. Thus, for processes that require high efficiency and stability, the degree of flexibility should be limited. The benefits of this concept primarily concern innovation and problem-driven tasks. In these cases, employees' strongest skills are leveraged if they are able to participate flexibly in different communities. Agile organisations are able to maintain stable processes whilst at the same time also being capable of adapting rapidly.[25]

The introduction of this type of organisation makes management's role more complex, since every employee is active in their own particular set of communities which, moreover, changes on a regular basis. IT-based collaboration platforms can provide transparency regarding employees' skills profiles and their involvement in communities, as well as facilitating communication and supporting assignment management. Management will also need to consider new technologies that enable these flexible communities by dramatically improving training speed via intuitive, in-context 3D and augmented reality solutions that guide workers safely through new operations.

Decision rights management

Two contrary mechanisms must be weighed up against each other when allocating the authority to make decisions or selecting the best decision-making procedure. Evidently, all the relevant information must be available in order to make the right decision. If decentralised decisions are taken, the local decision-makers will have better information about the actual circumstances, since they are closer to the facts. Achieving the same quality in a centrally taken decision would be more expensive because of the cost of conveying the information to the central level. On the other hand, decentralised decisions also generate costs either because they are not properly coordinated with each other and therefore potentially fail to consider what is best for the company as a whole or because they require additional management input to align them with the company's overall goals. Consequently, certain decisions must be taken centrally, for instance decisions concerning the company's strategy, whereas other decisions can be made more cost-effectively if they are decentralised.[26]

One of the benefits of Industrie 4.0 is better information availability. This means that even at a decentralised level it is possible to achieve transparency concerning the consequences of decisions and their alignment with the company's goals, enabling faster and better decentralised decision-making. Collective decision-making processes may also be employed. This involves

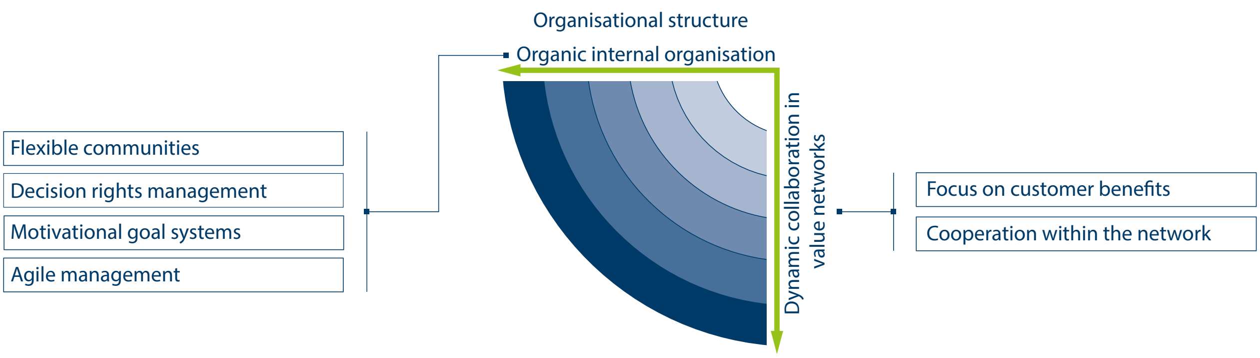


Figure 14: Capabilities of the structural area "organisational structure" (source: authors' own diagram)

25 | See McGrath 2012.
26 | See Jensen 1998.

bringing together the stakeholders in the company who are most competent to make decisions about the matter at hand.[27] For instance, the members of expert communities can be selected by conducting a kind of peer review of the candidates. Likewise, the potential of new development projects can be evaluated by the entire workforce rather than just a handful of managers. Companies must develop the capability to manage decision rights in a way that strikes the right balance between centralisation and decentralisation in order to maximise the effectiveness and efficiency of decision-making processes.

Motivational goal systems

Appropriate goal systems are needed to channel employees' greater autonomy and ensure that they remain focused on the company's overall goal of delivering customer value.[28] Overly specific goals that are measured one-dimensionally (e.g. the number of pieces produced) result in local optimisation and a "silo mentality". Instead, companies should introduce multi-dimensional goal systems that encourage employees to focus on process efficiency and continuous improvement. This calls for the development of completely new competencies such as financial controlling of communities or measuring the success of teams of experts. One example of a possible goal for an employee working in the field of development would be to require them to give a certain number of presentations at conferences attended by experts from outside of the company. This would provide a targeted means of encouraging them to subject their own ideas to critical evaluation by third parties.

Goal systems are closely linked to remuneration systems. These should not produce a purely transactional organisation where the only thing motivating employees is their pay.[29] The goal and remuneration systems should combine to provide employees with a degree of security and confidence that they are allowed to make the occasional mistake, whilst at the same time motivating them to contribute all the skills at their disposal to the organisation. This calls for the right mix of monetary incentives and non-monetary incentives such as training opportunities, development prospects and individual freedom.[30]

Agile management

Inflexible conventional development processes are unable to cope with the vague or changing requirements encountered in a dynamic environment. The required approaches are instead characterised by rapid prototype development, concrete (interim) results and high frequency feedback cycles with the stakeholders. One principle followed by agile development projects is to validate assumptions and hypotheses about the product or outcome as early as possible in a real-world environment. This involves focusing on a product's core functionality in order to produce what is known as a "Minimum Viable Product" (MVP).[31] MVPs are marketable products with restricted functionality that can be tested directly on the market, allowing systematic and rapid continued development of the product based on customer feedback.

These approaches can be applied not only to product and service development but also to the management of in-house projects. Physical manufacturing processes can be compared with digital models to identity opportunities for further improvement. Another example of one such process is the Scrum approach that originated in the field of software development.[32] This process accelerates continuous improvement initiatives with a 'start small and scale fast', data-driven approach to innovation.

Smart products with increasingly software-based functionality support this type of approach by enabling widespread data-based observation of real user behaviour so that product functionality can subsequently be enhanced, enabled or even disabled. An integrated system landscape also acts as a catalyst for the use of similar methods within the company itself. For example, changes in the product's design can be automatically communicated to all the relevant actors (e.g. in the form of revised work schedules).

4.3.2 Dynamic collaboration within the value network

Automated and seamless information exchange between different companies enables them to cooperate more dynamically and provides increased transparency with regard to the market. It also helps to reduce some of the barriers to greater flexibility, such as manual processes for enquiries, ordering and order processing. Operational visibility can be extended to include a supplier's production status and quality performance using today's IoT technologies. The result is a more efficient exchange of information, goods and services.

27 | See Schulte-Zurhausen 2014, p. 207ff.
28 | See Andersen et al. 2006.
29 | See Grunau 2014.
30 | See Sturm et al. 2011; Afshari/Gibson 2016.
31 | See Ries 2011.
32 | See Reichwald/Piller 2009.

Focus on customer benefits

According to the concept of core competence[33] or "strategic success positions"[34], companies should have a clear focus on a limited number of competencies in order to provide a unique proposition to the market. This concept is becoming even more important as markets grow more transparent and value creation becomes increasingly network-based and dynamic. The dynamic marketplace is an idea that is set to become hugely important. The suppliers that succeed in a transparent marketplace with well-functioning market mechanisms will be those who are best able to satisfy individual demand.

Specifically, companies have to determine how they can contribute to satisfying the end customer's needs. Even if the company doesn't itself deliver directly to the end customer, its product or service still forms part of the end customer's solution. The better the contributions made to this solution by the individual partners, the more successfully the companies in question will be able to differentiate themselves from the competition. An example would be a roller bearing manufacturer who concentrates not only on the immediate requirements of the machine manufacturer who is his direct customer but also on how his bearings are used by the machines' end user. By analysing the roller bearings' condition data using a cloud solution, he is able to provide the end user with additional services that help them run the machine more efficiently. This in-depth understanding of the end customer's requirements also makes him more attractive than the competition to his direct customer (the machine manufacturer), since it means that the overall solution provided by the machine fulfils the customer's needs more successfully.

Companies should be able to continually review their competencies and, if necessary, adapt them to changed circumstances. They must also establish exactly what role they should play in the value network. The targeted contribution of specialised competencies to an overall solution and the integration of several individual solutions in order to create a single overall solution can both be potentially successful strategies.

Cooperation within the network

Companies may consciously adopt a strategy either of outsourcing certain manufacturing and transport operations or of positioning themselves as suppliers of certain competencies to the

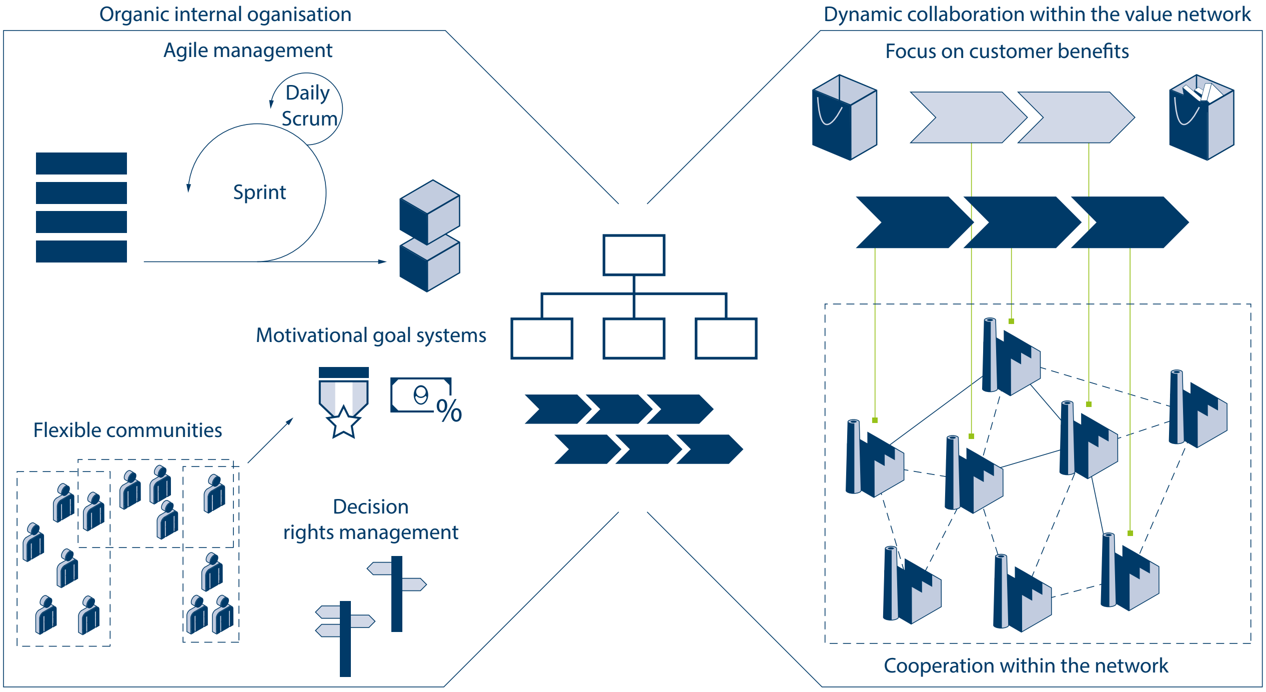


Figure 15 Capabilities required in the structural area "organisational structure" (source: authors' own diagram)

33 | See Prahalad/Hamel 1990.
34 | See Porter 1989; Pümpin/Amann 2005.

value network. Competency management refers to the systematic integration of different partners' competencies.[35] Companies that pool their competencies to meet specific needs are able to respond more rapidly to changing market requirements. By working together, the partners are able to develop and supply new products that they could never have delivered on their own or that would have first required them to embark on a lengthy in-house competency building process.

Flexible marketplaces that control the entire market already exist today for less complex, standard services (e.g. in logistics). One of the challenges is providing the very precise descriptions required for the services to be traded. In cases where companies that have not previously worked together wish to collaborate despite not yet having built up trust in each other, the effort required to negotiate a cooperation agreement is likely to outweigh the benefits of a short-term and potentially one-off collaboration.

Digital rights management plays an important role in this context. The seamless exchange of sensitive data, e.g. CAD models, is accompanied by the risk of the data not being used only for the intended purpose. Precautions must be taken to ensure that the right access to the data is granted for the defined purpose, e.g. to use a CAD model for a 3D-printed spare part only once and not several times.

4.3.3 Conclusion

Companies can get closer to the goal of a flexible, open marketplace by first of all cooperating more efficiently within existing networks. Horizontal order data integration and universal data exchange platforms (e.g. for joint development projects) can act as catalysts for cooperation.

Figure 15 summarises the key aspects of the structural area "organisational structure" once the "adaptability" stage has been attained. The left-hand side illustrates the internal perspective of the individual company. This is characterised by agile structures such as internal communities and agile management. The right-hand side illustrates the external perspective with the notion of a marketplace where value chains are configured on an order-by-order basis.

4.4 Culture

A company's agility is highly dependent on the behaviour of its employees. Experience with lean management in the 1990s and 2000s showed that the key to successful implementation of lean management throughout a business is to change the company's culture – in other words, to change the mentality of its employees. The same applies to the digital transformation into a learning, agile company in Industrie 4.0. Companies will be unable to achieve the desired agility if they simply introduce digital technologies without also addressing their corporate culture. Instead, they must begin by deciding how they want their company to do things in the future and which skills their employees will require. Only then should they identify and introduce the technologies needed to support the desired way of working. Digital assistance systems are a case in point. In itself, the introduction of such systems does not add value for a company. Before digital assistance systems can start to add value, the company must have a culture in which employees trust these systems and are prepared to accept their suggestions.

The necessary transformation of corporate culture is encapsulated in two key questions. Firstly, to what extent are employees willing to continuously review and adapt their own behaviour in response to a changing environment? The ideal scenario is for the entire workforce to be willing to change. Moreover, this **willingness to change** should not be confined to situations where changes are already being implemented. Importantly, it also means that people should look at their own environment and the corporate environment with open eyes, recognise when there is an opportunity or a need for change and initiate the relevant actions themselves. Willingness to change is the first principle of culture and is a key enabler of agility.

Secondly, to what extent do employees think that their actions should be guided by data- and fact-based knowledge? The ideal scenario is for them to believe that their actions should be entirely knowledge-based. The term "knowledge" encompasses any knowledge acquired through targeted observation, by chance, through data-based analysis or from practical experience. An environment characterised by trust and social relationships provides the basis for open, uninhibited knowledge sharing between employees. Consequently, the second principle of culture, **social collaboration**, helps to accelerate knowledge sharing within the company.

35 | See Schuh/Kampker 2011, p. 504ff.

4.4.1 Willingness to change

The first principle of the structural area "culture" is based on five capabilities that must be acquired by employees of learning, agile companies. These capabilities should not be treated as separate from each other – it is only when they are combined that they result in willingness to change.

Recognise the value of mistakes

Learning, agile companies attach great importance to mistakes. These companies have understood that learning and change processes can only be triggered by mistakes. Mistakes provide an opportunity to gain a better understanding of the company's processes and uncover previously unknown cause-and-effect relationships. The way a company deals with mistakes is therefore a key aspect of its corporate culture. Two fundamentally different approaches to mistakes exist. A negative attitude towards mistakes is reflected in a strategy based on the systematic avoidance of errors, strict penalties for making mistakes and the correction of errors as rapidly and unobtrusively as possible. Employees of companies where this culture prevails are not usually willing to disclose mistakes. This attitude inhibits their willingness to change. On the other hand, a culture that recognises the value of mistakes is characterised by open discussion of mistakes when they occur, systematic error documentation and a determination to find both the causes of the mistakes and their solutions. When investigating mistakes, it is critical to focus on understanding the causes rather than on finding out who is to blame.

Openness to innovation

A comprehensive understanding of how new technologies and approaches work is essential in order to ensure that they are integrated into the company in a way that adds value. The benefits of innovations are not always immediately apparent, since people will initially be unfamiliar with the underlying technologies because they have not previously been deployed in the company. One example is the use of data-based assistance systems in agriculture. Optimisation of the route taken by harvesters across the field can increase crop yields by as much as 20%. Various systems are now available on the market that are capable of computing the optimal route based on current environmental conditions and how full the harvester is. However, many farmers are reluctant to change the habits of a lifetime. Consequently, one agricultural machinery manufacturer decided to install their system free of charge on a trial basis. This allowed the farmer to see the direct benefits for himself and convinced him that it was time to start doing things differently. The trial demonstrated the value of "hidden" data and the information obtained from it. Openness to innovation and new ways of doing things is therefore an important capability that is required in order to initiate change and adopt the right measures, even if they may sometimes be rather unconventional.

Data-based learning and decision-making

Manufacturing companies' innovation cycles are getting shorter and shorter. In other words, they have less time to develop appropriate responses to changes in the business environment. This also means that errors must be spotted and their causes identified as quickly as possible. Rather than dealing with errors based on gut instinct, it is important to gain a data-based understanding of their causes so that the right measures can be taken to resolve them. Learning, agile companies are able to do this because they continuously monitor their value-added processes by capturing the relevant data. They then analyse this data, often comparing the digital model to the physical data and base any measures on the results of the analysis. Their employees have confidence in the data and are willing to learn from it and base their decisions on it. At Google, for example, employees' decisions about new measures are based almost entirely on data that has been captured and

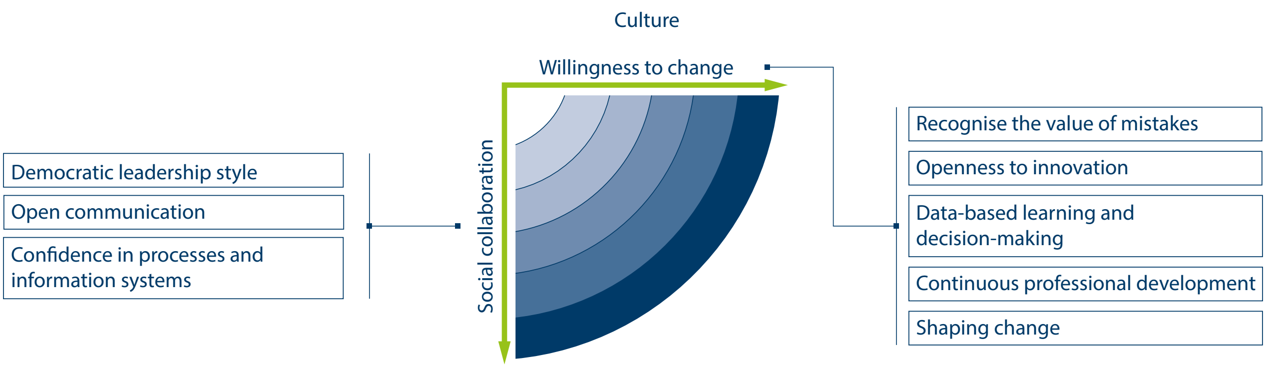


Figure 16: Capabilities of the structural area "culture" (source: authors' own diagram)

analysed. This is possible because the workforce is committed to continuous improvement and realises that decisions should not be based solely on one person's individual experience. They understand that data-based decision-making produces faster and better results than relying on the experience of individuals.

Continuous professional development

The digitalisation of industry is dramatically transforming the skill sets required by employees of manufacturing companies. Changes in manufacturing technology and the growing use of ICT mean that the required skills are changing more frequently. Whereas in the past there was a high demand for specialists with a lot of in-depth knowledge, in the future there will be a growing call for "multi-versatilists". These are employees who have an interdisciplinary understanding of interrelated processes and are capable of acquiring the necessary specialist know-how in a short space of time. Such employees understand that some of the skills and knowledge they have acquired in the past will only remain useful for a limited time. They are characterised by a desire to keep learning throughout their lives. The fact that they keep track of how their environment is changing means that they are quick to identify any new training requirements. They are therefore able to jointly formulate training programmes that address the required competencies whilst also meeting employees' needs.

Shaping change

The faster a company is able to provide an appropriate response to external events, the greater the benefits of the change for those affected by it. Consequently, the right changes must be initiated, implemented and completed as quickly as possible. It is therefore important to ensure that the initiative is taken by those employees who are best able to interpret the external event based on the knowledge at their disposal. Since these will often be the employees who work most closely with the system or machine in question, they may not necessarily have the authority to make decisions. Transferring decision-making powers, allowing employees greater leeway and giving staff with the relevant technical expertise the opportunity to share their knowledge are thus all important requirements. The critical factor, however, is for employees to understand that they too are responsible for shaping change. Rather than simply going along with change, they should be willing to initiate it of their own accord and be prepared to take the first step in order to make it happen.

4.4.2 Social collaboration

The second principle of the structural area "culture" is based on three capabilities. The principle of social collaboration helps to

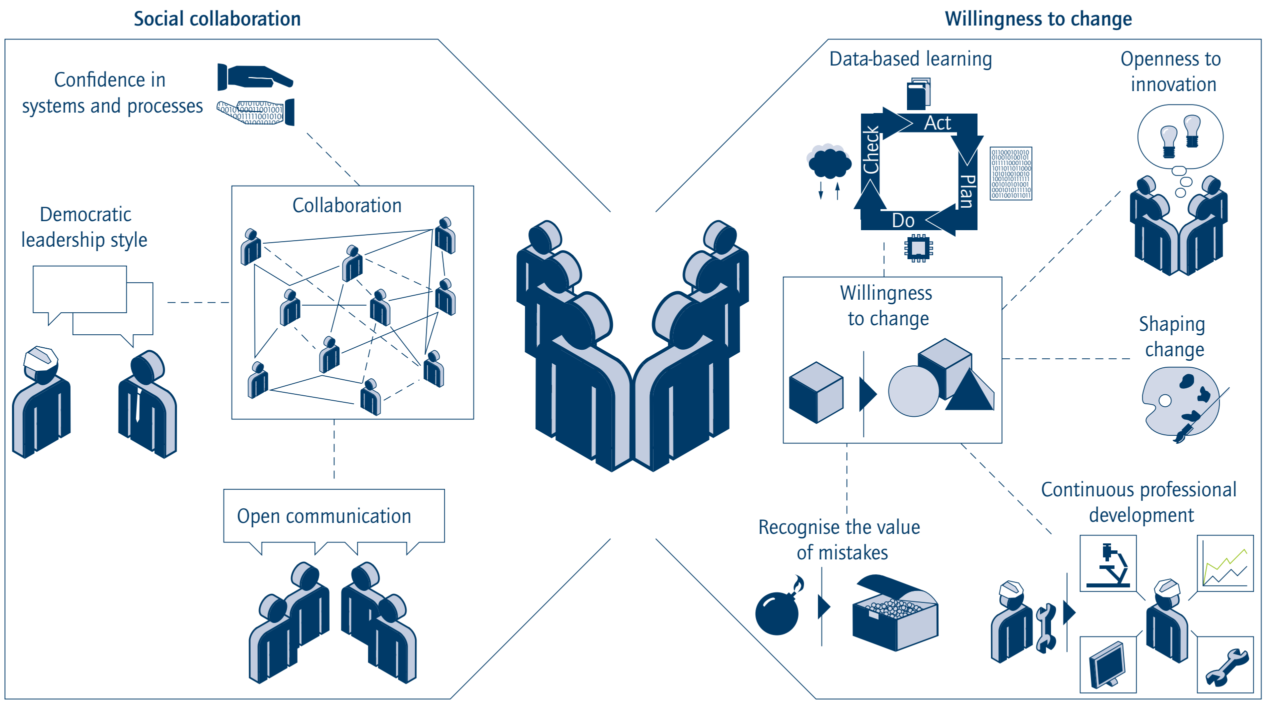


Figure 17: Capabilities required in the structural area "culture" (source: authors' own diagram)

accelerate knowledge sharing within the organisation and is enabled by the combination of these three capabilities.

Democratic leadership style

The increasing frequency of changes in the environment means that decisions about how to respond must be taken faster, but without impairing their quality. In addition to ensuring availability of the right knowledge so that the appropriate measures can be decided on, the decision-making processes for these measures must also be quicker. Adopting a more flexible approach to decision-making and giving people greater leeway creates the organisational framework for faster decision-making processes. In addition to creating the right framework, however, it is equally important for employees to have confidence in each other so that decisions are not only taken quickly but also implemented swiftly. Rather than merely seeing employees as resources, this requires management to value them as part of the community because of the competencies that they bring to the table. The underlying capability that makes this possible is a democratic leadership style.

Open communication

In order for companies to respond rapidly to unforeseen events in their environment, their employees should ideally have instant access to the necessary explicit and implicit knowledge. While explicit knowledge can be provided through the appropriate communication technology, the sharing of implicit knowledge calls for direct communication between the people who possess the knowledge and the people seeking it. For example, when production machinery is damaged or develops a fault, maintenance workers can access most of the production parameters that they need to analyse via the relevant information systems (MES/ERP systems). However, operators' firsthand experience of working with the machines and information that is not captured by sensors, such as changes in noise levels, can only be shared directly between employees. Consequently, the workforce must stop thinking in terms of rigid hierarchies and abandon the "us and them" mentality. Employees have acquired the capability of open communication if, having taken on board the fact that openly sharing knowledge and working together to achieve a vision increases the total sum of knowledge, they then also act accordingly. Once the organisation's entire workforce is willing to share knowledge with everyone, it becomes possible to significantly accelerate learning processes within the company.

Confidence in processes and information systems

The lessons learned from the introduction of information technology since the 1970s teach us that it is not enough to focus exclusively on functional requirements. The acceptance and systematic use of information technology and systems can only be ensured if the affected personnel are included in the change process right from the outset and can actively participate in shaping the changes. As well as involving employees in the design of the relevant information systems, the entire workforce must understand that the benefits of these information systems will only be realised if they are systematically used by everyone. The fact that employees of learning, agile companies have confidence in the chosen processes and information systems enables rapid sharing of documented knowledge, in a role-base, contextual way. This confidence is based on the fact that the employees understand how the information system makes its decisions and recognise the concrete benefits of its recommendations. At the same time, however, they keep a critical eye on the system and are keen to enhance it with their own knowledge in the interests of continuous improvement.

4.4.3 Conclusion

Figure 17 illustrates the characteristics that a manufacturing company's culture should possess once it has reached the "adaptability" maturity stage. Social collaboration exists between employees and with customers and partners. Confidence in systems and processes results in high process stability. People are willing to document their acquired knowledge and share it with others. The democratic leadership style values people for the contribution they make and there is a culture of open communication. Moreover, the workforce is both receptive and willing to change. They learn systematically from the captured data, are open to innovative approaches and participate in shaping change processes. Employees are also conscious of the need to continuously develop their skills and competencies. While mistakes are still made, people recognise that they are valuable because they have the potential to trigger improvements.

5 Functional areas in the business

In the acatech Industrie 4.0 Maturity Index, the capabilities described above are investigated separately for each of a company's functional areas. The specific maturity stage of each capability may be different for different functional areas and the business processes contained within them. In the following sections, the vision of a learning, agile company is applied to the five functional areas (see Figure 18). The description of the key capabilities for each area is broken down into the four structural areas. To make the model easier to use, the functional areas are examined at the level of their constituent business processes.

5.1 Development

A fundamental change is occurring in the development function of manufacturing companies, as the technological, cultural and organisational aspects of Industrie 4.0 increasingly penetrate corporate processes. The conventional design theory of Pahl & Beitz as well as the approach to mechatronic systems design set out in the VDI 2221 and VDI 2206 standards are giving way to the realisation that not all of the customer's requirements are known or can be properly addressed at the beginning of the development process. Rather than starting with a rigid finished product in mind, it is becoming increasingly common to work with a product vision that can keep evolving in response to new requirements and automated change requests throughout the development phase and even once the product is in use.

Advanced Systems Engineering is an integrated product development methodology that underlines the importance of autonomy, dynamic networking, product-service systems and the socio-technical interactions between new technological systems.[36] The AdWiSE project, which is coordinated by acatech, is helping to strengthen German companies' competencies in this area by developing a strategy and connecting the relevant actors.[37]

Resources

In addition to highly-qualified personnel who adopt an interdisciplinary approach to their work, the main resources of the development function are the products. The company retains its focus on the product even after it has delivered it to the customer – field data from product users provides input for targeted further development. This requires products to be capable of capturing and transferring data. Furthermore, some product functionalities can be updated and changed via software. This offers the company new opportunities for efficient, short-cycle release management – new functionality can still be added to products long after they have been launched on the market and faults can be fixed rapidly.

Additive manufacturing processes constitute another valuable resource. The systematic implementation of this technology in the relevant processes is critical to ensuring that prototypes and primotypes can be built rapidly and cost-effectively.

Information systems

Development is carried out by small interdisciplinary teams on virtual platforms that enable cross-company collaboration. This requires a complete digital model of the development process to be built up in a primary system such as the PLM system. This approach provides a transparent picture of function tests and component dependencies, requirements and changes throughout the entire product lifecycle. The model constitutes the product's digital shadow. Change requests relating to the documented dependencies can be automated, thereby significantly improving the responsiveness of the product development process.

Systems integration is not confined to the field of development. Cooperation with other directly and indirectly connected areas ensures availability of the latest product documentation and product feedback. The data is also made available to the production department so that production workers have access to the latest versions of the design documents such as the drawings and parts lists. This ensures that the production and assembly teams are directly informed about any changes to the product.

Organisational structure

Agile methods such as Scrum are revolutionising the development process not only in software development but throughout all disciplines so that requirements can be implemented through short iteration cycles focused on individual aspects of the product vision. Rather than getting bogged down in the theoretical specification of the product's details at the beginning of the development process, the aim is to test the key hypotheses about the product as quickly as possible. "Primotypes" deliver concrete insights based on actual use and user feedback. Rather than merely validating functionality, these prototypes which are

36 | See Heinz Nixdorf Institute, https://www.hni.uni-paderborn.de/ase/.

37 | See acatech AdWiSE, https://www.acatech.de/projekt/adwise-vernetzung-der-akteure-zur-disziplinuebergreifenden-entwicklung-komplexer-vernetzter-sozio-technischer-systeme-fuer-die-wertschoepfung-von-morgen-advanced-systems-engineering/.

manufactured with near-series processes implement the "Minimum Viable Product" concept. This allows customer feedback to be incorporated into the development process to deduce specific customer requirements, significantly reducing both the time taken to implement the product and the associated costs. Getting it wrong early on in the process and learning from these mistakes is an integral part of this approach.

The design decisions for primotypes are based on data as well as assumptions. Real data from people who have used the product and customer requirements documented by marketing & sales are supplemented by formal design, production and assembly knowledge to enable continuous data analysis with a view to improving product quality and cost-effectiveness.

Interdisciplinary collaboration beyond the development phase is also critical in order to succeed. Approaches like system engineering and service engineering are becoming increasingly important to enable systematic learning from the product over the whole product lifecycle.

Modular product design promotes collaboration with other companies in networks. Partners develop function modules right up to the point where they are ready for series production. In this case too, however, they are initially only given very general specifications (e.g. product dimensions or target price), with the detailed specifications being elaborated during the course of the development process. It is important to ensure that the people working on the modules adopt an interdisciplinary approach in order to enable the development of innovative and efficient solutions. The goal is to accelerate the product industrialisation process by building individual production-ready modules.[38]

Case Study: Lockheed Martin

The technology company Lockheed Martin leverages a "Digital Tapestry" – a fully integrated electronic domain that weaves together all elements of the product development process into a seamless digital environment. This enables the entire enterprise (engineering, IT, suppliers, manufacturing etc.) to benefit from a complete digital product definition. The Digital Tapestry is helping to spur innovation and collaboration. This program has allowed Lockheed Martin to identify problems and refine solutions while still in the concept design phase – resulting in significant savings in both time and money.

Lockheed Martin uses the Digital Tapestry in many programs in their Space Systems organization, including the Orion Spacecraft. The Orion Spacecraft ushers in the next generation of human space exploration by taking up to four astronauts to deep space and safely back to Earth. During a live test with NASA, Lockheed Martin was able to capture over 200 GB of data, including data such as cabin pressure and temperature from the prototype and feed this data back into the design cycle to improve the design for future missions.

Culture

The radical transformation of the development process leads to a change in the company's culture. From an early stage, customers are presented with ideas, concepts and primotypes that are purposely not yet fully developed so that disfunctionalities are detected as early as possible in the process. This approach also informs the "Minimum Viable Product" concept which involves

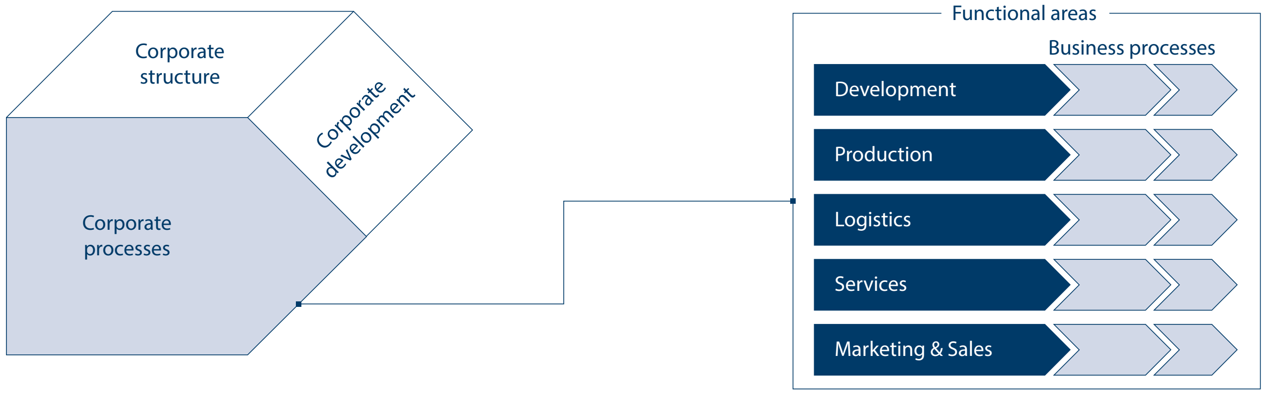


Figure 18: Overview of functional areas (source: based on Boos et al. 2011)

38 | See Kampker 2015.

building a product as quickly as possible with only the most essential functionality. This mentality is very different to the perfectionist approach that is prevalent today. Intentionally allowing mistakes to happen and dealing with them constructively will thus be important aspects of culture in the future.

The company's culture is also characterised by the notion of internal and external collaboration. Ideas are judged based on their usefulness rather than on where they come from. A range of different sources are drawn on, including e.g. close cooperation with and observation of customers or involvement in communities of practice with other companies and institutions.

5.2 Production

Production will remain the heart of tomorrow's manufacturing companies as manufacturing and assembly techniques continue to develop. The way that products are processed and manufactured has to be aligned with the customer's requirements concerning the product, making new value creation strategies necessary. Companies will focus on their core competencies. The fact that they will form part of a genuine value creation network will lower the degree of vertical integration. This will also enable higher flexibility in terms of the product features and the portfolio to meet customers' individual needs. The partnering ecosystem will also provide higher customer focus as well as more cost-efficient ways of producing the desired (tailored) goods. In order to maintain the competitiveness of companies in high-wage countries, it will be essential to ensure efficient resource utilisation by enabling better decision-making on the shop floor.

Resources

Resources are key to value creation in manufacturing companies. Information and communication technologies can be used to enhance formerly isolated or entirely passive objects, creating cyber-physical systems (CPS). Connecting these objects to each other and to the relevant information systems provides a completely new level of transparency in the production environment, ultimately resulting in the creation of a digital shadow. Real data from the shop floor is captured by a multitude of sensors, processed into information and used to make decisions. Assistance systems or actuators in the CPS are then used to implement the chosen measures.

Throughout the entire value creation process, the products and materials in the field of production are clearly allocated to a specific order. Real-time order progress information is available anytime, anywhere. Target completion is monitored continuously and reliable predictions are provided regarding the impacts of any variance. Operators must be able to safely operate multiple machines as these grow increasingly complex. Analysis of the captured data enables production planning and control personnel to discover new connections between planning variances and manufacturing processes. Experts such as supervisors, foremen and shift leaders are able to concentrate on making non-automated decisions and working with data scientists to investigate the causes of faults.

Additive Manufacturing

While in the past engineering and manufacturing has been a sequential process chain, both now get an integral capability, allowing dramatic improvements in throughput time and flexibility. For example, Aircraft engine components were oftentimes difficult to manufacture as they are consisting of several parts that needed to be produced each with an individual process, assembled and welded and are finally subject to intense quality assurance procedures. With additive manufacturing those components can be be designed with less constraints from the production process and can be optimized towards their purpose. Right at the end of the design process they can be printed directly – requiring almost no human preparation or interaction. Design changes are effective immediately and do not require lengthy and cost intensive production process changes.

Information systems

In the manufacturing environment, too, information systems will continue to provide the basis for the management and allocation of human and technological resources. However, monolithic structures are set to disappear, with data coming instead from a single source of truth but accessible to various applications. Dynamically configurable planning systems will perform complex computations to maximise productivity independently of the resource management function. The results will be delivered to workers on the shop floor context-sensitively and on the end device of their choice. Employees will also have access to a suite of role based and task-specific apps.

In tomorrow's value networks, companies' business applications will not only be used in-house but will also be connected to the systems of their suppliers, customers and other partners in the value network. This data will be included in the single source of truth. The high availability and quality of the data provided will improve the responsiveness of all the actors. Just-in-time and just-in-sequence strategies will become even more important, allowing inventory levels to be reduced, work-in-progress to be optimised and supply chain latency to be minimised. Data scientists and process experts will work together using data analysis techniques to examine quality data, machinery and equipment condition data and process parameters for converting this information into knowledge. The objective will be to find the optimal resolution of the goal conflict between logistics costs and logistics performance.

Organisational structure

Seamless collaboration between the partners is key to creating value in a network. The companies involved in a value network provide the machine capacity and manufacturing expertise. In exchange, they gain access to external expertise and capacity. Core competencies in specialised manufacturing processes and personnel capacity are advertised on virtual marketplaces and priced dynamically based on the company's current capacity utilisation. Conventional supply chain hierarchies are partially replaced by non-hierarchical competency- and capacity-based structures.

Shop floor teams are no longer assigned to work on just a few tasks, but instead form part of an interdisciplinary team responsible for the product as a whole. A regular dialogue on product-specific issues between members of different departments such as quality control, component manufacture and production planning and control promotes knowledge sharing and continuous learning. This also allows e.g. change requests from the engineering function to be easily implemented in production. Employees are empowered to make their own decisions in order to enable faster response times. Both new and old solutions are documented, jointly evaluated and converted into structured knowledge. Employees are evaluated based on their willingness to share knowledge as well as on the results of their work.

Culture

Changing a company's culture in relation to mistakes can unlock significant potential in the field of manufacturing. Discussing mistakes allows weaknesses in the corresponding processes to be identified and potentially resolved. It can prove useful to borrow certain ideas from lean production – the implementation of continuous improvement processes and shop floor management techniques can help to promote open discussion of mistakes. As the tasks that employees are required to perform grow increasingly complex and diverse, they will need to become more proactive in sharing best practices with each other. Appropriate moderation and documentation is urgently necessary in order to make this possible. In the future, shop floor workers in particular will encounter IT systems far more frequently.

Case Study: CNB

CNB is a leading manufacturer of customizable yachts. The company integrated the whole information flow from engineering to manufacturing and vice versa. While using a PLM-system to maintain all relevant product information in a unified system of record, CNB also uses IoT solutions to digitally link information from engineering to manufacturing, e.g. with dashboards or digital assembly instructions. Using a 3D digital mockup of the product, engineers are able to choose parts to be put into the engineering Bill of Materials (eBOM) of the single yacht. Then information in the eBOM is transformed automatically to the manufacturing Bill of Materials (mBOM) in a format that the manufacturing stakeholders need to build the product on the assembly line. This gives CNB the digital continuity that enables parallel design and manufacturing planning. Early access to information stored in the eBOM cuts down on the cycle time required to manufacture a product. With these new processes, it has become easier for CNB to deliver a boat on time and on budget.

5.3 Logistics

In terms of logistics, the priority for learning, agile companies is to meet the needs of customers, consumers and users of their services. Logistics is understood as an integrative, crosscutting function both inside and outside of the company[39]. The primary function of logistics remains unchanged: to ensure the availability of the right goods, in the right quantity, in the right place, at the right time, for the right customer and at the right cost.[40] This applies not only to finished goods but also to spare parts, in order to ensure the availability of sold machines and assets. However, the paradigm shift caused by Industrie 4.0 will bring about a fundamental change in the associated information flow and this will affect the entire

39 | The changes described here refer primarily to logistics in manufacturing companies rather than the changes affecting logistics providers.
40 | See Gudehus 2010, p.3.

logistics delivery process. As a result, logistics will become more closely integrated into the overall value chain and there will be a shift towards service-oriented logistics on demand.[41]

Resources

Materials handling equipment and packaging are fitted with information technologies such as beacons or Real Time Location Systems (RTLS) technology. Technical resources such as forklift trucks are able to autonomously identify themselves, determine their current location and capture data about their status and the transported goods. Complete information transparency exists regarding the storage period, location and quantity of stored goods. The connected goods autonomously communicate relevant information, for example about their condition. Autonomous vehicles are also included in this communication process. They are capable of decentralised data aggregation, allowing them to interact with the other transport units in order to autonomously perform vehicle and order management functions using agent-based swarm intelligence.

Information systems

Service-oriented logistics on demand relies on integrated information systems that enable continuous communication between sender and recipient. Integrated IT systems allow the recipient, e.g. the production department, to request an item autonomously. The fact that transport units, autonomous vehicles and warehousing facilities are connected to these systems creates a digital shadow of the real world. This virtual model of all the process components enables simulation-based control using real-time data, as well as automatic monitoring and real-time documentation. The system compares the current process status against the target data. In the event of variance, the plan is revised and the current process sequences are adjusted autonomously. The changes are communicated to the relevant vehicles or displayed to their drivers so that they can be implemented with immediate effect.

Organisational structure

The crucial organisational change in the field of logistics will be the greater decision-making autonomy available to logistics partners. Decentralised decision-making facilitates leaner logistics planning, since connectivity ensures that the actors have access to a virtual model of the processes. An in-depth understanding of upstream and downstream processes allows logistics to be closely integrated into the value network. Instead of logistics operations being allocated to individual people or vehicles, logistics platforms are used to identify who is best placed to perform a given operation. The decision is based on criteria such as current location, earliest possible delivery time and cost. Eventually these developments will lead to even more fourth-party logistics business enterprises. The last mile could be served by the lowest bidder at the exact moment of demand.

Culture

The workforce accepts the fact that last-minute changes to logistics processes will become increasingly frequent. Everybody understands that all logistics decisions are entirely data-based in order to enable continuous process improvement. The effectiveness of these data-based decisions is ensured by the systematic use of information technology and systems. Employees also contribute their own knowledge to logistics processes. They are able to learn from the data by combining IT and knowledge management.

5.4 Services

Industrie 4.0 offers manufacturing companies new opportunities to profitably develop the various parts of their business. The traditional activity of only selling products that the company has made itself is increasingly being superseded by new, solution-driven service business models. In the future, companies will transform from a transaction-based sales model, in which the customer owns the product, to a "product-as-a-service" model. This allows customers to have access to the product but pay based on product usage or some other metric tied to the value the product delivers to the customer (e. g. Rolls Royce "Power by the Hour" for aircraft engines).

Customers' specific and at times diverse needs are no longer predominantly addressed by products but by individually configurable data-based services that combine products made both in-house and by external partners. A simple example is a predictive maintenance service based on a remote connection to the product. The ability to tailor services to the customer's specific requirements results in more effective service delivery and strengthens the relationship between customer and service provider, enabling the establishment of a long-term relationship. The service provider assumes more responsibility for individual steps in the customer value creation process, thereby becoming more closely integrated into this process. Examples include service level agreements, output-based business models and revenue models where the service provider receives a share of the revenue from productivity gains. One thing that all of the above have in common is that they involve payment of a fee to the manufacturer based on a subscription model.

41 | See ten Hompel 2013.

Resources

Smart, connectivity-enabled products on which services are performed or which are used to provide services are a key requirement for data-based services. These products are characterised by the ability to capture their own operating and environmental data, process it themselves – at least to a certain extent – and send it to the service provider. This does not only apply to the products that a company has made and sold itself. Instead, it is once again important to think in terms of an ecosystem in which all the products in a value chain contribute their own data. Whilst this does of course include the company's own products that are used at different stages of the value creation process, it also includes third-party products. The successful providers will be those that manage to aggregate the data for all of the relevant manufacturers and customers, thereby gaining control of the "digital control point".

It is only by capturing and aggregating data in this way that companies can transform their business models as described above so that they are more closely integrated with their customers' processes and able to establish subscription- and outcome-based models. For instance, a company needs accurate condition and operating data for a product if it wishes to guarantee its availability with a minimum of risk and at a competitive price. An example is Trane, an HVAC manufacturer that is now able to guarantee high performance climate control in entire buildings because it can monitor its equipment remotely, 24/7. Likewise, companies wishing to optimise the way a factory runs must be able to relate data from upstream and downstream process stages to their own products.

Information systems

The service dimension is added to the established Product Lifecycle Management approach. In addition to product development data, the system also incorporates data generated or required in connection with the product's use and the delivery of product-related services. This creates a comprehensive digital shadow of the product, with different, domain-specific views of the data (e.g. services and development) to provide service visibility and real-time product data. There are many applications for this single source of truth. For example, a service technician in the field always has access to the most up-to-date product documentation and can also view the service history and access operating and condition data for diagnostic purposes. Meanwhile, the development team can use operating data to inform the product's continued development.

The question of the IT infrastructure must also be addressed. Software-defined platforms are not dissimilar to the service platforms used to organise service delivery as described in the previous section. Software-defined platforms provide the environment for data aggregation and the provision of data-based services. Providers are already positioning themselves in this area today and are offering operation of the relevant infrastructure as a service. Third-party companies can use these platforms to connect their smart products and provide their customers with individual app-style services.

Organisational structure

In the future, customers will have access to highly specific service bundles, depending on their particular needs. These will be delivered by an individually configured group of companies in the value network and may comprise both conventional services involving personal contact with the customer and automated, data-based services. For instance, the manufacturer's technical service may be combined with highly specialised third-party services such as data analytics. The service platforms that enable this collaboration form the lynchpin of these new data-based services.

One of the main challenges companies are facing is to define exactly which role they should play themselves. This may be anything from a specialist in an individual service or provider for a platform right up to a service platform integrator or operator.

The boundaries of the industry in which the company operates will become less clearly defined and each company will need to decide how much it wants to expand its service activities. For example, mining equipment manufacturer Joy Global expanded the scope of its services from individual pieces of equipment to the optimisation of the entire equipment fleet in a mine. At a technical level, this leads to the question of whether a company should itself develop competencies in specific areas (e.g. operating an IoT platform) or buy in the required competencies.

Culture

Since service technicians are continually being confronted with new problems and finding solutions to them, the aggregation of their collective know-how harbours huge potential. It is therefore especially important that service technicians should be willing to share and document their knowledge. In the future, social communication between service technicians involving the use of communication platforms to discuss solutions will be an important means of systematically building up knowledge. The advent of advanced technologies such as augmented reality (AR), virtual reality (VR) and speech recognition will radically change the way service technicians operate and share knowledge. Text-based technical information and knowledge sharing is notoriously ineffective, leading to low productivity among service technicians across industries. The ability to visualise repair instructions in context and issue voice-based commands, including speech-to-text, will enable faster learning and enhanced collaboration.

These new insights from the service function can then be used e.g. in development projects to help ensure that customer requirements are incorporated into the development process from an early stage. The closed loop between development and service also ensures that products are designed for efficient servicing. If service technicians are viewed as an interface with the customer, then as well as channelling feedback on marketing and sales related issues they can also carry out certain marketing and sales functions themselves.

Case Study: Trane

Aftersales services are becoming increasingly important for heating, ventilation and air conditioning products in homes and buildings. This is also true for manufacturing company Trane, which worked with cinema operators in the US to develop a real-time climate control system that responds to current ticket sales and film showing times. The available data is used to find the optimal temperature for each auditorium and set the thermostat accordingly.

The use of smart technology allows the company to avoid a scenario where as soon as something stops working it has to be repaired as quickly as possible. Instead of this, data is now used to determine when a motor is at risk of failing and calculate how long it will continue working for. This information makes it possible to send a maintenance technician to work on the right unit at the right time – and to conclude better service agreements. "For every dollar we make from product sales, we have the potential to make twelve dollars in aftersales. At present, our product and service turnovers are virtually identical. But services are much more profitable", says company spokesperson Per Bollom. Like many other manufacturers, Trane expects that the share of its top and bottom line accounted for by services will continue to grow.

5.5 Marketing & Sales

The main objective of an agile company is to be strategically focused on systematically understanding and fulfilling its customers' requirements. The marketing & sales function plays a key role in this regard by actively guiding customers towards a buying decision in what is known as the "customer journey". Integrating individual processes to create a personalised, end-to-end digital buying experience adds value for the customer, generating customer loyalty from an early stage and placing the customer at the centre of the company's business.

Resources

In addition to human resources, the most important resources for marketing & sales are the production machinery and equipment and the products themselves. It is only possible to make a proposition to a customer if punctual delivery can be guaranteed based on reported and projected machine and equipment capacity. Moreover, feedback data about product use provides new insights into customer requirements and makes it possible to check that the product is being used correctly.

Information systems

The agile company is able to actively control the contact points on the customer journey. This is possible thanks to the comprehensive, high-quality data obtained both from the CRM and ERP systems and from market research which enables the identification, analysis and evaluation of individual customers. Data analytics techniques are used to assess business relationships with customers in terms of economic criteria, based on their historical order data, internal company data and external environmental factors. The results are then broken down into product requirement and behaviour profiles. Collaborative filtering is employed to analyse typical customer behaviour patterns and make context-sensitive predictions about what they are likely to do next. Foreseeable sales, current capacity utilisation, customer histories and market information are combined so that dynamic pricing models can be reliably used for revenue management purposes. Customers can be offered new contract models that, for instance, exclude verifiable warranties or offer improved after-sales service thanks to product feedback generated during use. The data-based approach allows the integration of bespoke service propositions with the customer's processes and the supply of the relevant information to the customer to be realised so seamlessly that the customer shows minimal interest in alternative products.

Organisational structure

In the future, marketing & sales will concentrate on those channels that are a seamless fit for the customer journey and can be most closely integrated with the customer's processes. The goal is to be "top of mind" at the forefront of the customer journey, to reach the customer at the optimal time, often as early as possible, and to be ready and waiting for them when they make their purchase decision. This can be partly achieved by electronically connecting companies' own sales platforms to their customers' systems so that marketing and sales operations on the supplier side can be automated. Online product visualisations support the customer by compiling targeted information and automatically displaying the details they need to make their purchase together with supplementary information about the product. Digital collaboration platforms provide new ways of interacting with customers. For instance, customers can use these platforms to communicate their individual product design requirements which can then be passed on directly to the development or production teams.

Culture

A radical transformation occurs in marketing & sales culture, particularly as far as the silo mentality of sales representatives is concerned. Customer contacts are managed centrally in a CRM system that provides a single source of truth. Sales representatives feed their implicit knowledge about the customer's current problems into the development process and are willing to act as important internal collaboration partners. They have a positive attitude towards the constant change that characterises agile companies and engage actively in driving continuous improvement. They are also accepting of innovative data-based products and service bundles that call for new marketing and sales strategies.

6 Application of the acatech Industrie 4.0 Maturity Index

Companies can use the acatech Industrie 4.0 Maturity Index to help them plan their own specific Industrie 4.0 development path and prepare them for the step-by-step transformation into an agile company. The Index facilitates a clearer picture of the understanding and status quo of digitalisation within the company and of the measures required by individual parts of the business or processes to enable targeted synchronisation across the entire company.

6.1 Principles of application

The use of the Index comprises three successive stages (see Figure 19). The first stage is the identification of the current maturity stage in the different functional areas. Stage 2 involves the company identifying the target development stage that it wishes to attain at the end of the transformation process, based on its corporate strategy. This involves analysing its existing Industrie 4.0 capabilities by functional and structural area. A gap analysis is used to identify the missing required capabilities that it still needs to develop. These will depend on the current development stage ascertained in stage 1 and the target state that the company wishes to achieve by the end of the transformation. Finally, stage 3 involves formulating actions and incorporating them into a roadmap with a view to developing the capabilities identified in stage 2.

6.1.1 Stage 1: Identification of the current Industrie 4.0 maturity stage

The identification of the current Industrie 4.0 maturity stage is based on the Industrie 4.0 capabilities outlined in Chapter 4. The capabilities are determined on the basis of the business processes in the functional areas. They are evaluated using a questionnaire that rates the capabilities for each process. Each question has multiple-choice answers that are linked to the six development stages.

An example is provided in Figure 20 below. This part of the questionnaire relates to a process in the functional area "production". It evaluates the extent to which the value of mistakes is recognised in the structural area "culture". The multiple-choice answers allow a clear rating to be assigned to the capability in question.

The evaluation takes place on site at the company. A tour of the site allows an initial impression to be formed of how the processes work. The processes are then evaluated in a workshop where the status quo is analysed based on the order management process. The scores for the capabilities belonging to the relevant principle are then aggregated and shown for each individual process. The acatech Industrie 4.0 Maturity Index uses concentric circles (see Figure 19) to represent the maturity stages of the four structural areas. The greater the radius of the circle, the greater the maturity of the manufacturing company as determined by the evaluation.

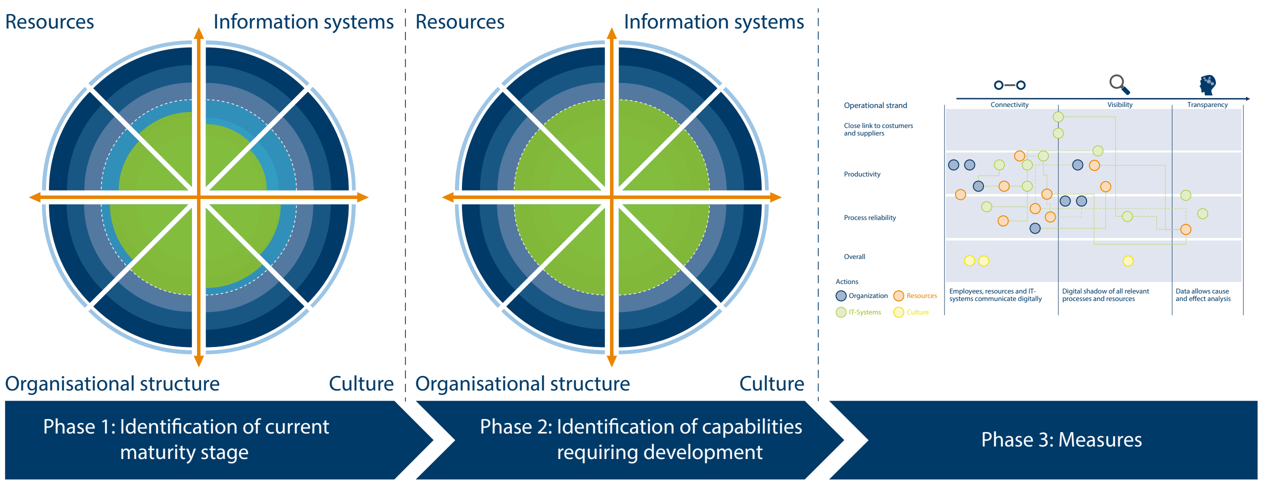
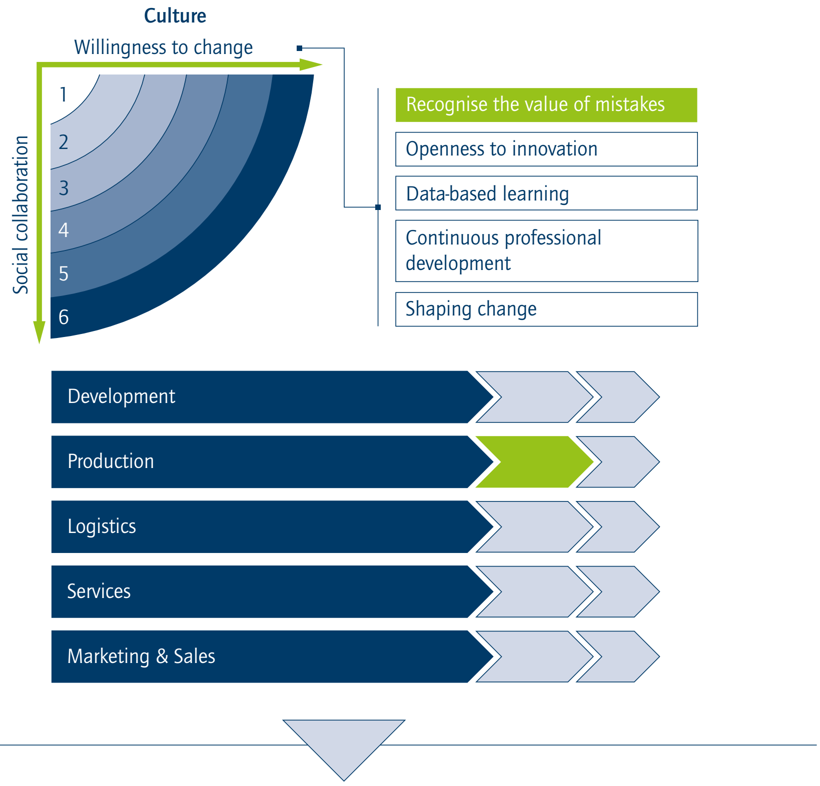


Figure 19: Application of the Maturity Index (source: authors' own diagram)



What is employees' attitude towards mistakes?

1 ☐ Errors lead to finger-pointing and are often covered up. There is no internal discussion of errors to try and prevent people from taking the blame or being blamed by others.

2 ☐ Company policy recognises the importance of tracing the causes of errors and ensuring that everyone learns from them, for instance by discussing them in one-on-one interviews. However, a lack of resources or funding means that this policy does not usually translate into systematic error documentation and follow-up.

3 ☐ Employees strive to avoid errors; they observe the quality management guidelines on standardised error documentation and are willing to discuss errors within their own department.

4 ☐ Employees see errors as a valuable resource and want to identify and understand them; there is no finger-pointing and there are no cover-ups – when errors occur they are addressed in a constructive spirit. The measures taken to address major errors are documented, forming a new standard that is integrated into the relevant process.

5 ☐ Errors are communicated openly. The focus is on understanding the cause and on shared learning rather than on assigning blame. For example, details of errors are displayed publicly in order to raise awareness about them.

6 ☐ All errors without exception are analysed and appropriate measures taken to address them. Moreover, the effectiveness of these measures is evaluated so that they can be adjusted as necessary.

Figure 20: Example question (source: authors' own diagram)

6.1.2 Stage 2: Identification of capabilities requiring development

The scores for the individual processes can then be aggregated to produce an overall score for each functional area and for the company as a whole. The visual depiction of the scores makes it possible to rapidly determine the average maturity stage and flags up differences in the development stage of the four structural areas. The main aim of understanding how the different structural areas compare to each other is to ensure that they are developed at a similar rate. If, as in the following example, the "resources" and "culture" structural areas score more highly than the other two structural areas, this means that they possess capabilities that cannot be taken advantage of because the relevant capabilities are lacking in the "information systems" and "organisational structure" structural areas (see Figure 21).

It is therefore recommended that, as a general rule, companies should begin by addressing those areas where action is required in order to attain the same maturity stage for all four structural areas so that the full benefits of this maturity stage can be realised (achieve maturity stage consistency). There may be some operating areas or functions where the majority of the available benefits may be achieved without the requirement for balance and equal levels of maturity among the four components. These could include complex logistical operations, the success of which is determined mostly by organisational effectiveness, or predictive maintenance improvements where the most critical role is played by effective information systems. Once the required levels of maturity and alignment have been achieved, the company can move on to address the additional actions required to attain the target state (attain a higher maturity stage). This two-stage process is illustrated below in Figure 22.

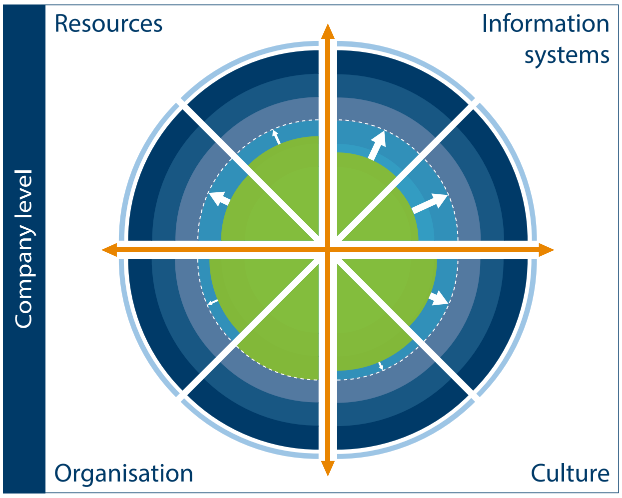


Figure 21: Aggregation at company level (source: authors' own diagram)

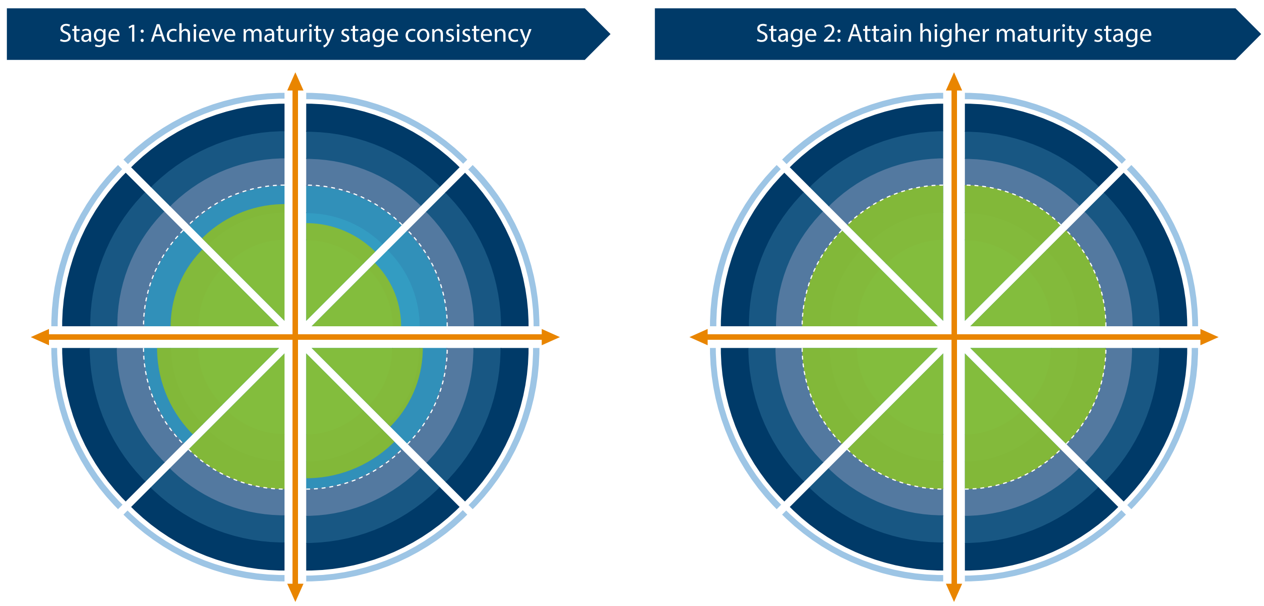


Figure 22: Defining the areas where action is required (source: authors' own diagram)

6.1.3 Stage 3: Identifying concrete measures

The next step is to formulate measures addressing the areas identified as requiring action. The necessary measures can be deduced from the missing capabilities in the four structural areas. The fact that individual processes have been evaluated makes it possible to target these measures very precisely. The company is now in a position to produce a development roadmap and start implementing the measures as soon as possible.

The measures for individual processes can be assigned to functional areas depending on which functional areas these processes belong to. Moreover, measures that are thematically very similar are clustered together under "operational strands". The roadmap sets out the measures for each operational strand, such as process reliability, productivity or customer/supplier relationships, in a sequence that supports the progressive raising of the Industrie 4.0 maturity level (see Figure 23). If a comparison of the roadmaps against the measures for individual plants or parts of the business reveals that there are a lot of similar measures, the results of these smaller units can be consolidated to create an overall roadmap for the entire business.

The measures for both of the stages that must be completed in order to reach the target state – i.e. maturity stage consistency and attainment of a higher maturity stage – are first of all plotted along the time axis so that they can be prioritised, coordinated with each other and implemented in a logical sequence.

The measures can also be evaluated using a cost-benefit matrix. An indicator system was employed to assess the benefits, with an indicator being assigned to each capability. The development of the relevant capability is reflected in an improvement in the indicator score, allowing the benefits of a particular measure to be evaluated. The assessment of the costs is left up to each individual company.

6.2 Quantify the benefits

Indicators are used to quantify the benefits of Industry 4.0 applications for enterprises. The basic idea is to link well-established indicators with the impacts of Industrie 4.0. By linking the indicators with the acatech Industrie 4.0 Maturity Index, the results of the assessments can be depicted with concrete numbers (see Figure 24). This allows enterprises to understand how an improved maturity level affects certain indicators.

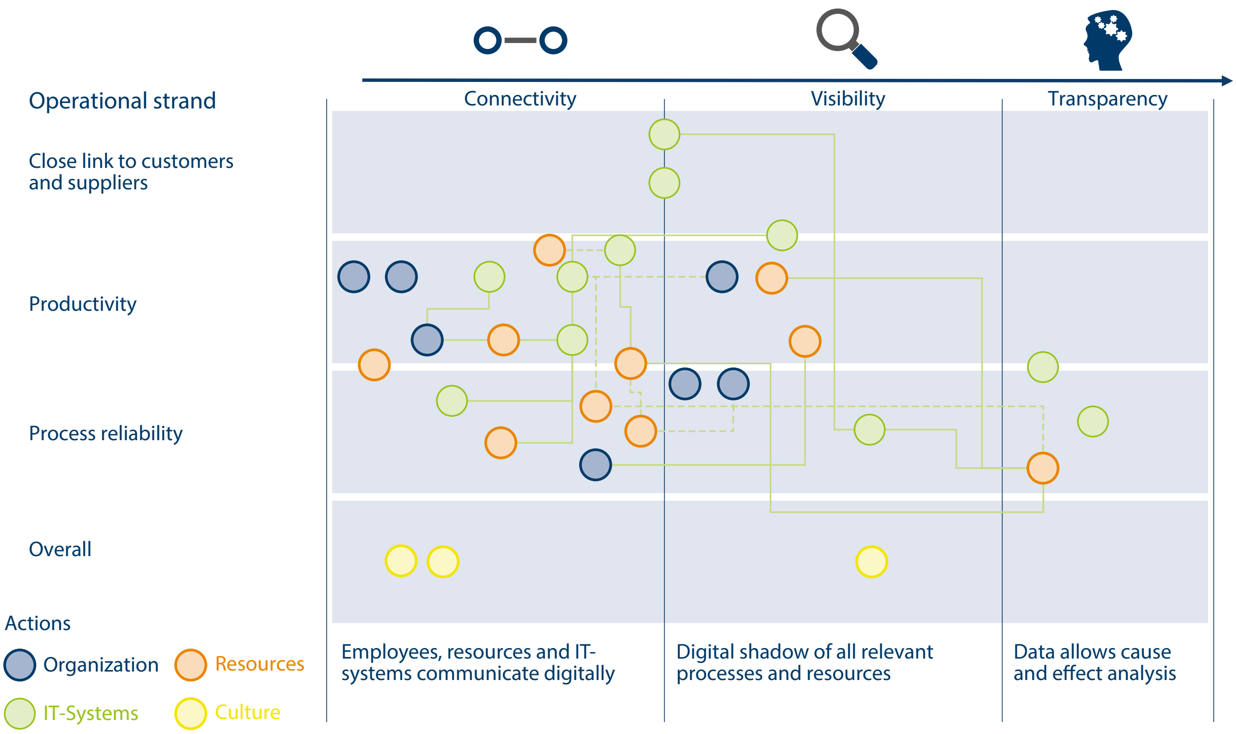


Figure 23: Identification of measures (source: authors' own diagram)

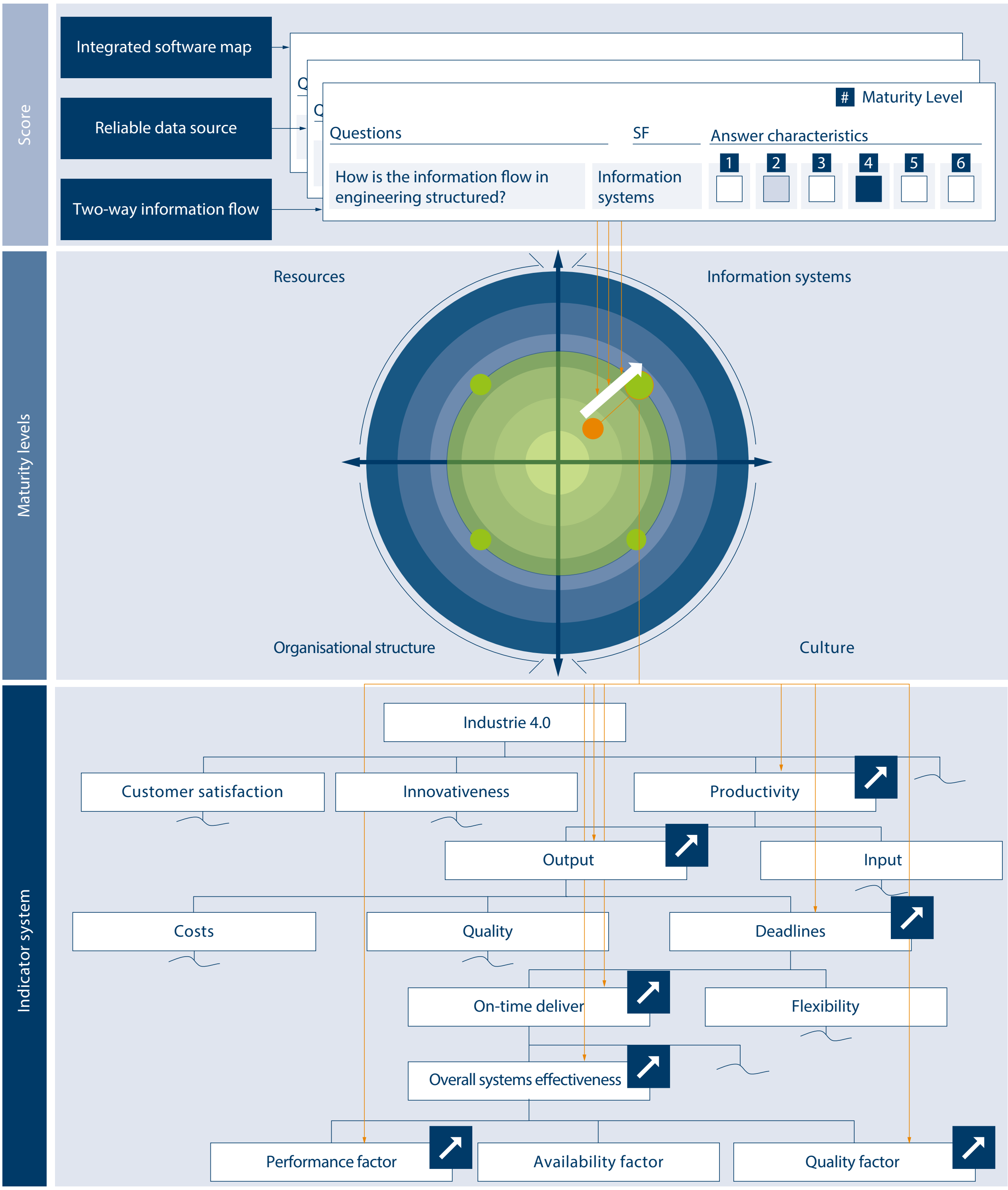


Figure 24: Linkage between key figures-classification scheme and the acatech Industrie 4.0 Maturity Index (source: authors' own diagram)

The indicator classification system is necessary in order to evaluate the benefits of Industrie 4.0 applications.[42] Complex coherences, e.g. the benefits of self-optimising production processes, need to be explained in a way that can be easily understood. A self-optimising production process can improve the overall effectiveness of a machine and can result in improved adherence to delivery deadlines by lowering the rate of unexpected failures. This can have a positive impact on the output of an enterprise and its overall productiveness. The short example makes it clear that the indicator classification system needs to portray the relationships between the indicators themselves.[43] Established indicators were therefore examined and transformed into a hierarchical structure.[44] The maturity level of the enterprise is shown in the topmost layer, while the innovation capacity, productivity, etc. are shown underneath. Productivity is the ratio between a company's output and input. Measurable figures, e.g. the performance factor of a machine, are shown in the lowest layer. The impacts of Industrie 4.0 applications can be directly assigned to figures in the lowest layer. When one of these figures is affected, the implications for figures in the higher layers can be visualised. To estimate the benefits of a higher maturity level, the figures for the lowest layer are connected with the capabilities of the Maturity Index.

6.3 Example application in a company

The acatech Industrie 4.0 Maturity Index was validated at Harting AG & Co. KG's Espelkamp site in early August 2016. Harting manufactures industrial connectors, device connection technology and network components. In 2016, it employed approximately 4,300 people across a total of 43 sales companies and 13 manufacturing facilities. The company's head office is located in the town of Espelkamp and this is also the location of its largest manufacturing facility.

Harting drew up a detailed inventory of the processes in all of the relevant functional areas. In addition to interviews with experts in the individual functional areas, a site visit was carried out during which the process of making of a standard product was demonstrated so that the transitions between different departments and the availability of information on the shop floor could be evaluated.

Harting has already done a lot of work in the field of Industrie 4.0, especially in its manufacturing facilities. The upgrading of its IT infrastructure over the past few years and the systematic provision of feedback from the shop floor have made it possible to create a digital model of the production environment in the company's information systems. Individual pilot projects in different production areas are generating an in-depth understanding of the relevant technology. The company has also learned a lot from the process of integrating these pilot projects with its existing operational processes. By way of example, one of the pilot projects involves automatically detecting the condition of die cutters using structure-borne sound.

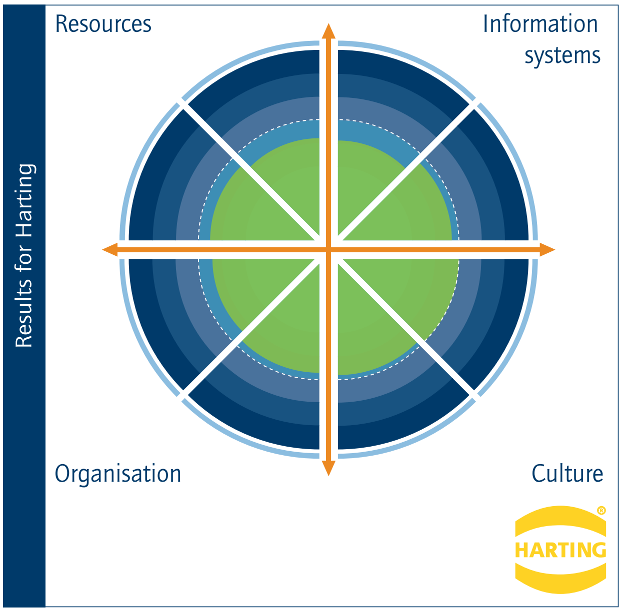


Figure 25: Assessment for Harting (source: authors' own diagram)

The assessment found the company to have attained the "visibility" maturity stage (stage 3) due to the implementation of these Industrie 4.0 pilots in the value chain and the existence of a digital model as illustrated by Figure 25. Having established the status quo, measures were formulated to ensure that all aspects of this maturity stage attained a consistent level before taking action to help the company reach the next maturity stage.

42 | See Obermaier 2016.
43 | See Lingnau und Brenning 2015, pp. 455–460.
44 | See Pfeifer et al. 2014.

Harting's roadmap contained over 30 measures across the different functional areas, with the incremental goal of attaining maturity stage 4 "transparency". Measures to attain maturity level 5 and 6 are not included in the current roadmap. These actions will be integrated into the results of a subsequent assessment.

One measure in the functional area "production" involves integrating and rolling out the existing pilot projects across the entire manufacturing process. Since the pilots are running on separate production lines, they are currently only resulting in local process improvements. These improvements are isolated and fragmented, since their potential is not being leveraged across all of the production lines (see left-hand side of Figure 26). Consequently, this measure aims to integrate the individual pilot projects into an end-to-end process in order to take full advantage of the Industrie 4.0 potential. This involves choosing an integrated approach for a particular product or product group and rolling out the pilot project across the entire value creation process. As well as the deployment of additional sensors, this also includes integration with the relevant operational and decision-making processes in order to enable data-based decision-making (see right-hand side of Figure 26). The experience gained from implementing the pilot projects is used to inform their roll-out on a larger scale.

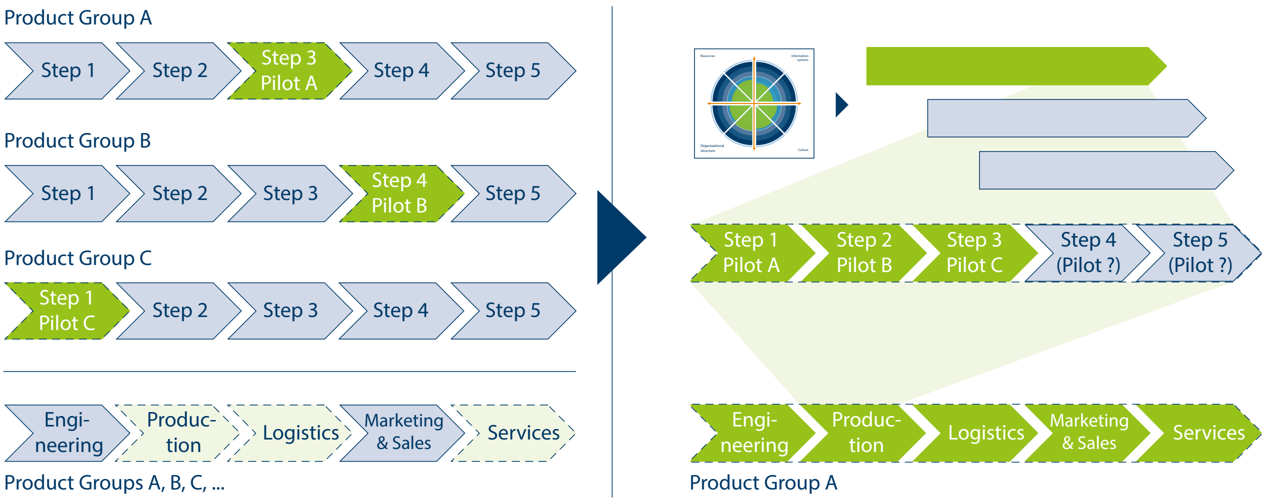


Figure 26: Example of measures identified (source: authors' own diagram)

7 Conclusion

The term Industrie 4.0 first appeared in a publication in 2011 and has since then been used to describe the widespread integration of information and communication technology in industrial production. However, the term is sometimes misinterpreted and focusing only on a technological perspective. In fact, companies also need to transform their organisational structure and culture. The ultimate goal is to become a learning, agile company capable of continuous, agile adaptation to a changing environment.

The acatech Industrie 4.0 Maturity Index provides companies with guidance for carrying out this transformation into a learning, agile company. The index presents six consecutive development stages for four key areas of every company. Each stage delivers additional benefits to the company. The index can be used to develop a digital roadmap precisely tailored to the needs of each individual company in order to help them master the digital transformation across all involved relevant business units.

In the future, the model and the study's findings can be used to develop tools and best practices that assist companies with the concrete shaping of the transformation. This should be done separately for different industrial sectors in order to ensure that the recommendations are as specific as possible and to reflect the differences between individual industries. Consequently, further validations should be carried out to investigate the specific characteristics of different sectors and types of business. It is important for the model to keep receiving additional input so that it can continue to develop in the spirit of continuous learning. In addition to further validations, we hope that this input will also come from a dialogue with interested partners in research and industry.

References

acatech 2016
acatech (Ed.): *Kompetenzen für Industrie 4.0. Qualifizierungsbedarfe und Lösungsansätze* (acatech POSITION), Munich 2016.

acatech AdWiSE
acatech: *AdWiSE – Vernetzung der Akteure zur disziplinübergreifenden Entwicklung komplexer vernetzter sozio-technischer Systeme für die Wertschöpfung von morgen* (Advanced Systems Engineering). URL: https://www.acatech.de/projekt/adwise-vernetzung-der-akteure-zur-disziplinuebergreifenden-entwicklung-komplexer-vernetzter-sozio-technischer-systeme-fuer-die-wertschoepfung-von-morgen-advanced-systems-engineering/ [Retrieved: 17.02.2020].

Afshari/Gibson 2016
Afshari, L./Gibson, P.: "How to Increase Organizational Commitment through Transactional Leadership". In: *Leadership & Org Development,* 37: 4, 2016, pp. 507–519. DOI: 10.1108/LODJ-08-2014-0148.

Andersen et al. 2006
Andersen, B./Henriksen, B./Aarseth, W.: "Holistic Performance Management: an Integrated Framework". In: *International Journal of Productivity and Performance Management*, 55: 1, 2006, pp. 61–78.

Auer 2018
Auer, J.: *Industrie 4.0 – Digitalisierung mildert demografische Lasten,* Deutsche Bank Research (Ed.): Deutschland-Monitor, 29.10.2018.

Bauernhansel et al. 2016
Bauernhansel, T./Krüger, J./Reinhart, G./Schuh, G: *WGP-Standpunkt Industrie 4.0*, Wissenschaftliche Gesellschaft für Produktionstechnik Wgp e. V. (Ed.), 2016.

Boos et al. 2011
Boos, W./Völker, M./Schuh, G.: "Grundlagen des Managements produzierender Unternehmen". In: Schuh, G./Kampker, A. (Ed.): *Strategie und Management produzierender Unternehmen. Handbuch Produktion und Management 1*, Berlin, Heidelberg: Springer Verlag (VDI-Buch) 2011, pp. 1–62.

BMWi 2015
Bundesministerium für Wirtschaft und Energie (Ed.): *Industrie 4.0. Volks- und betriebswirtschaftliche Faktoren für den Standort Deutschland. Eine Studie im Rahmen der Begleitforschung zum Technologieprogramm*, 2015.

Burns/Stalker 2001
Burns, T./Stalker, G. M.: *The Management of Innovation*, Oxford: Oxford Univ. Press 2001.

Ciupek 2016
Ciupek, M.: "Neues Leben für alte Maschinen". In: *VDI nachrichten*, 29.04.2016 (17). URL: http://www.vdi-nachrichten.com/Technik-Wirtschaft/Neues-Leben-fuer-alte-Maschinen [Retrieved: 31.03.2017].

Grunau 2014
Grunau, J.: *Führungsstile in der Diskussion: Transaktionale und transformationale Ansätze im Vergleich,* 2014.

Gudehus 2010
Gudehus, T.: *Logistik*, Berlin, Heidelberg: Springer Verlag 2010.

Hackathom 2002
Hackathom, R.: "Minimizing Action Distance". In: *DM Review,* 12, 2002, pp. 22–23.

Heesakers et al. 2019
Heesakers, H./Schmitz, S./Kuchenbrod, U./Woelbeling, C./Zimmer, T.: "The ISPE Pharma 4.0™ Operating Model's - Pharma-Specific Maturity Index". In: *ISPE Special Reports,* May/June, 2019. URL: https://ispe.org/pharmaceutical-engineering/may-june-2019/ispe-pharma-40tm-operating-models-pharma-specific-maturity# [Retrieved: 12.02.2020].

Heinz Nixdorf Institute
Heinz Nixdorf Institute, Paderborn University: *Advanced Systems Engineering.* URL: https://www.hni.uni-paderborn.de/ase/ [Retrieved: 11.02.2020].

IEC
IEC 62443: *Network System and Security*.

Jassawalla/Sashittal 1999
Jassawalla, A. R./Sashittal, H. C.: "Building Collaborative Cross-functional New Product Teams". In: *Academy of Management Perspectives*, 13: 3, 1999, pp. 50–63. DOI: 10.5465/AME.1999.2210314.

Jensen 1998
Jensen, M. C.: *Foundations of Organizational Strategy*, Harvard University Press 1998.

Kagermann/Nonaka 2019
Kagermann, H./Nonaka, Y. (Eds.): *Revitalizing Human-Machine Interaction for the Advancement of Society. Perspectives from Germany and Japan* (acatech DISCUSSION), Munich 2019.

Kampker 2015
Kampker, A. (Ed.): *Wir müssen früh scheitern, um schneller erfolgreich zu sein. Effizienzsteigerung im Industrialisierungsprozess am Beispiel des StreetScooter*, Aachen: Apprimus Verlag 2015 (Return of Engineering).

Lingnau/Brenning 2015
Lingnau, V./Brenning, M.: "Komplexität, Flexibilität und Unsicherheit-Konzeptionelle Herausforderungen für das Controlling durch Industrie 4.0". In: *Controlling,* 27: 8/9, 2015, pp. 455-460.

Love/Roper 2004
Love, J./Roper, S.: "The Organisation of Innovation: Collaboration, Cooperation and Multifunctional Groups in UK and German Manufacturing". In: *Cambridge Journal of Economics*, 28: 3, 2004, pp. 137-157.

McGrath 2012
McGrath, R. G.: "How the Growth Outliers Do It". In: *Harvard Business Review*, January/February, 2012, pp. 110–116.

Muehlen/Shapiro 2010
Zur Muehlen, M./Shapiro, R.: "Business Process Analytics". In: Vom Brocke, J./Rosemann, M. (Eds.): *Handbook on Business Process Management. Strategic Alignment, Governance, People and Culture,* second edition (International Handbooks on Information Systems), New York, Berlin, Heidelberg: Springer 2010, pp. 137-157.

Obermaier 2016
Obermaier, R.: *Industrie 4.0 als unternehmerische Gestaltungsaufgabe,* Wiesbaden: Springer Fachmedien 2016.

Pfeifer et al. 2014
Pfeifer, T./Schmitt, R. (Eds.): *Masing Handbuch Qualitätsmanagement,* 6th revised edition, Munich, Vienna: Carl Hanser Verlag, 2014

Porter 1989
Porter, M. E.: "From Competitive Advantage to Corporate Strategy". In: Asch, D./Bowman, C. (Eds.): *Readings in Strategic Management*, London: Macmillan Education UK 1989, pp. 234–255.

Prahalad/Hamel 1990
Prahalad, C. K./Hamel, G.: "The Core Competence of the Corporation". In: *Hardvard Business Review,* 86, 1990, pp. 79–91.

Pümpin/Amann 2005
Pümpin, C./Amann, W.: *SEP. Strategische Erfolgspositionen; Kernkompetenzen aufbauen und umsetzen*, Bern: Haupt 2005.

Reichwald/Piller 2009
Reichwald, R./Piller, F.: *Interaktive Wertschöpfung. Open Innovation, Individualisierung und neue Formen der Arbeitsteilung*, Wiesbaden: Gabler Verlag/GWV Fachverlage GmbH 2009.

Ries 2011
Ries, E.: *The Lean Startup. How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses*, New York, NY: Crown Business 2011.

Schuh et al. 2014
Schuh, G./Reiher, S./Heinitz, K./Soellner, R.: "Steigerung der Kollaborationsproduktivität durch cyber-physische Systeme". In: Bauernhansl, T./ten Hompel, M./Vogel-Heuser, B. (Eds.): *Industrie 4.0 in Produktion, Automatisierung und Logistik*, Wiesbaden: Springer Fachmedien 2014, pp. 277–296.

Schuh et al. 2017
Schuh, G./Brecher, C./Klocke, F./Schmitt, R. (Hrsg): *Internet of Production für agile Unternehmen*: AWK Aachener Werkzeugmaschinen-Kolloquium 2017, 18.–19. May 2017, Aachen: Apprimus Verlag 2017.

Schuh/Kampker 2011
Schuh, G./Kampker, A.: *Strategie und Management produzierender Unternehmen*, Berlin, Heidelberg: Springer Verlag 2011.

Schulte-Zurhausen 2014
Schulte-Zurhausen, M.: *Organisation*, Munich: Vahlen 2014.

Sturm et al. 2011
Sturm, M./Reiher, S./Heinitz, K./Soellner, R.: "Transformationale, transaktionale und passiv-vermeidende Führung. Eine metaanalytische Untersuchung ihres Zusammenhangs mit Führungserfolg". In: *Zeitschrift für Arbeits- und Organisationspsychologie*, 55: 2, 2011, pp. 88-104.

ten Hompel 2013
ten Hompel, M.: "*Neue vernetzte Wege in der Logistik*", BMWI. Autonomik – Autonome und simulationsbasierte Systeme für den Mittelstand, Berlin 2013.

Yin 2009
Yin, R. K: *Case Study Reaearch. Design and Methods*, Thousand Oaks [et al.]: Sage Publications 2009.

About acatech – National Academy of Science and Engineering

acatech advises policymakers and the general public, supports policy measures to drive innovation, and represents the interests of the technological sciences internationally. In accordance with its mandate from Germany's federal government and states, the Academy provides independent, science-based advice that is in the public interest. acatech explains the opportunities and risks of technological developments and helps to ensure that ideas become innovations – innovations that lead to greater prosperity, welfare, and quality of life. acatech brings science and industry together. The Academy's Members are prominent scientists from the fields of engineering, the natural sciences and medicine, as well as the humanities and social sciences. The Senate is made up of leading figures from major science organisations and from technology companies and associations. In addition to its headquarters at the acatech FORUM in Munich, the Academy also has offices in Berlin and Brussels.

For more information, please see www.acatech.de

Authors/Editors:

Prof. Dr.-Ing. Günther Schuh
FIR e.V. at RWTH Aachen University
Campus-Boulevard 55
52074 Aachen | Germany

Prof. Dr.-Ing. Reiner Anderl
Department of Computer Integrated Design
Technical University of Darmstadt
Otto-Berndt-Straße 2
64287 Darmstadt | Germany

Prof. Dr.-Ing. Roman Dumitrescu
Heinz Nixdorf Institute
Paderborn University
Fürstenallee 11
33102 Paderborn | Germany

Prof. Dr. Antonio Krüger
German Research Center for Artificial Intelligence, DFKI
Stuhlsatzenhausweg 3
66123 Saarbrücken | Germany

Prof. Dr. Michael ten Hompel
Fraunhofer Institute for Material Flow and Logistics IML
Joseph-von-Fraunhofer-Straße 2-4
44227 Dortmund | Germany

Series editor:

acatech – National Academy of Science and Engineering, 2020

Munich Office
Karolinenplatz 4
80333 Munich | Germany
T +49 (0)89/52 03 09-0
F +49 (0)89/52 03 09-900

Berlin Office
Pariser Platz 4a
10117 Berlin | Germany
T +49 (0)30/2 06 30 96-0
F +49 (0)30/2 06 30 96-11

Brussels Office
Rue d'Egmont/Egmontstraat 13
1000 Brussels | Belgium
T +32 (0)2/2 13 81-80
F +32 (0)2/2 13 81-89

info@acatech.de
www.acatech.de

Recommended citation:
Schuh, G./Anderl, R./Dumitrescu, R./Krüger, A./ten Hompel, M. (Eds.): *Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies – UPDATE 2020* – (acatech STUDY), Munich 2020.

Bibliographical information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographical data is available online at http://dnb.d-nb.de.

Coordination: Joachim Sedlmeir, Dr. Johannes Winter
Edited by: Birgit Obermeier, Alrun Straudi
Translation: Joaquin Blasco
Layout concept: Groothuis, Hamburg
Cover photo: Florian Küttler/Westend61
Conversion and typesetting: Fraunhofer IAIS, Sankt Augustin

The original version of this publication is available at www.acatech.de

As well as promising faster and more efficient manufacturing processes, digitally connected industrial production in the context of Industrie 4.0 also provides opportunities to design and implement new business models. Companies need to be extremely agile, flexible and good at learning in order to adapt dynamically to a disruptive environment. In addition to building and refining the necessary technological (artificial intelligence) and data-based (big data and cloud solutions) capabilities, companies must also make the relevant adjustments to their organisational structure and corporate culture.

This publication is an update of the original acatech STUDY published in 2017. Featuring updated text and illustrations, it describes the concept of the acatech Industrie 4.0 Maturity Index, which provides companies with guidance for their own individual transformation process. The Index is based on a six-stage maturity model that analyses the capabilities in the structural areas of resources, information systems, culture and organisational structure that are required by companies operating in a digitalised industrial environment.