acatech COOPERATION

Using the Industrie 4.0 Maturity Index in Industry

Current challenges, case studies and trends

Günther Schuh, Reiner Anderl,
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German Research Center for Artificial Intelligence
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Executive Summary

The lessons learned from three years of using the acatech Industrie 4.0 Maturity Index in industry make it plain that the fourth industrial revolution cannot be accomplished simply through the implementation of individual, isolated prototypes. German manufacturing industry has now recognised this fact and is focusing on the development of systematic, rigorously structured transformation programmes aimed at delivering clear value added.

The acatech Industrie 4.0 Maturity Index in use

Since the publication of the acatech STUDY three years ago, the Industrie 4.0 Maturity Index has proven its worth as a tool offering practical guidance on how to achieve a structured digital transformation. The widespread use of the Index and extensive interest in the themes it addresses indicate that companies are increasingly intent on adopting an integrated approach to Industrie 4.0. The Index has been used for everything from drawing up systematic roadmaps for the digital transformation of individual manufacturing sites to the synchronisation of different sites and the formulation of a global digitalisation strategy. The Index can also be used to measure and manage progress towards the digital transformation and to carry out technical due diligence for corporate acquisitions. These examples illustrate the significant value added that can be generated by using the Index.

80% of the companies that took part in a survey by the Industrie 4.0 Maturity Center said that they have attained "connectivity", the second of the Index's six maturity stages. In other words, they are currently working on the measures needed to achieve "visibility", which is the first stage of Industrie 4.0. Just 4% of companies said that they have already achieved this next stage. These are the Industrie 4.0 pioneers or champions among the companies that took part in the survey.

Areas currently requiring action

The widespread "digital diseases" afflicting many companies can be cured or mitigated by adopting the structured approach outlined in the acatech Industrie 4.0 Maturity Index. These diseases include the lack of common standards for machine controllers, fragile information system integration, a reluctance to engage in interdepartmental cooperation and inadequate employee involvement in change processes.

At present, companies should therefore focus on the systematic implementation of common data platforms throughout the business, for example using cloud-based Industrial Internet of Things (IIoT) platforms that enable the aggregation of data from different sources such as business application systems, machine controllers and sensors. These platforms also provide a framework for developing individual visualisations and applications. The lessons learned so far from the application of the Industrie 4.0 Maturity Index in industry show that there are a number of serious general challenges in all four structural areas. These include end-to-end data delivery across the entire value chain in the "resources" area, the use of edge and cloud computing to break down the hierarchies of the automation pyramid in the "information systems" area, and the use of agile methods and promotion of employee involvement in the "organisation" and "culture" areas.

The use of the Index by the major global automotive supplier ZF Friedrichshafen AG illustrates the value of consolidating the results of individual sites at group level in order to synchronise digitalisation activities. HARTING KGaa was already involved in the 2017 acatech STUDY and has since achieved the third maturity stage by producing guidelines, creating a digitalisation team and integrating its machinery in order to improve data delivery for its employees. The increase in overall equipment effectiveness achieved through the transformation programme at specialty chemicals manufacturer Kuraray demonstrates that the Index can have a positive impact in a variety of different industries. At Kuraray, for example, the adoption of an IIoT platform has contributed to the implementation of Industrie 4.0. The case study of a chocolate factory illustrates how the Index's main use in the food industry is to increase efficiency and output.

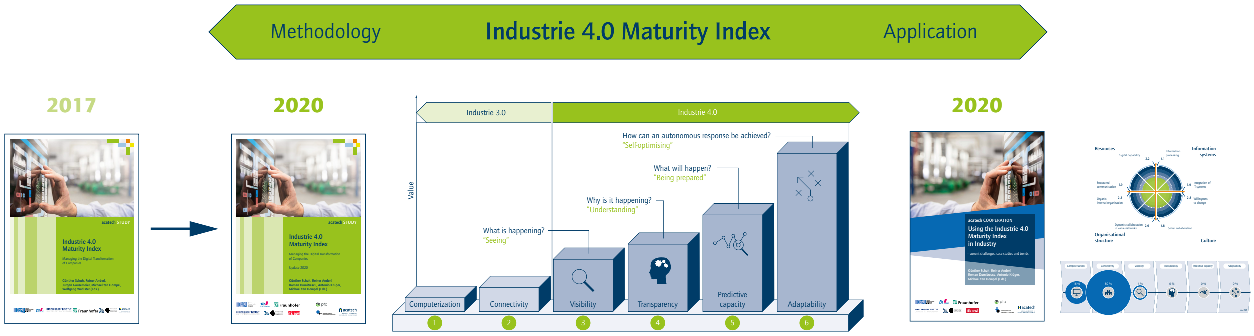
Areas requiring future action

While it has delivered successful results over the past three years, the use of the Industrie 4.0 Maturity Index also raises a number of medium-term strategic issues. In the future, manufacturing industry will be increasingly concerned with the "predictive capacity" and "adaptability" maturity stages. Here, the focus will be on industrial applications of artificial intelligence and the sociotechnical interactions between humans, technology and organisations. New HR management concepts are also becoming more and more important in the context of the digital transformation.

The ultimate goal is to become a learning, agile company capable of adapting continuously and dynamically to a disruptive environment. In particular, unexpected developments such as the coronavirus crisis show companies the importance of a high degree of adaptability and resilience.

Having already proven its practical value in industry, the Industrie 4.0 Maturity Index provides a structured, integrated framework for tackling these future challenges, too.

This companion publication 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. This publication complements the 2020 update of the acatech Industrie 4.0 Maturity Index that revisits the methodological basis by incorporating a number of editorial changes into the STUDY of 2017 together with updates to some of the illustrations (see Figure 1).



acatech STUDY update

- Editorial changes
- Updated content
- Revised illustrations

Case study publication

- Status quo of studied companies
- Presentation of case studies
- Description of next steps/trends

Figure 1: Study update and companion publication with case studies

1 Introduction

"What's so new about Industrie 4.0? We have been using information technology in our factories for decades." Only a few years ago, this was still typical of the responses given by German companies when asked about Industrie 4.0. "Industrie 4.0" was already a buzzword when acatech published the first edition of its Industrie 4.0 Maturity Index in 2017. However, people weren't really sure what the systematic rollout of Industrie 4.0 in a manufacturing company would actually involve or what the benefits might be. With its Industrie 4.0 Maturity Index, acatech created a tool that provides the answers to these questions. The Index was clearly focused on the step-by-step evolution of manufacturing companies into "Industrie 4.0 companies". After all, most companies want to continue using and upgrading their existing, established facilities, since they are simply not in a position to build new, state-of-the-art factories. This is consistent with the fundamental Industrie 4.0 concept of establishing and systematically learning from integrated, automated information flows throughout a company's value chain.

Many companies were already working on isolated prototypes such as the implementation of predictive maintenance prototypes or proof of concept projects for autonomous forklift trucks. While these projects undoubtedly raised awareness of the opportunities presented by the technology, their piecemeal nature failed to properly implement the systematic approach of Industrie 4.0, which aims to achieve real-time integration of entire value chains. As well as providing a framework for individual projects, the acatech Industrie 4.0 Maturity Index sets out the fundamental technical requirements and the organisational and cultural changes required to support them. It provides a guide that companies can use to determine their own status quo and start their journey towards becoming a learning, agile organisation.

The Industrie 4.0 transformation is inextricably linked to the development of the digital business models known as smart services. However, the Industrie 4.0 Maturity Index focuses on optimising companies' value chains through digital integration – it is aimed at improving the digital maturity stage of the company's internal processes. Once they have achieved digital connectivity in their core industrial processes, businesses will be in a position to develop digital services and collaborate with partners to build ecosystems offering joint smart services.

Today, we are witnessing how the two trends of Industrie 4.0 and digital business models can combine to generate synergies. Internal business processes such as development, production and service can systematically learn from data generated throughout these internal processes and while the company's products are being used by their customers. Many companies have already made significant strides towards the vision of becoming a learning, agile business by combining digitally connected processes with digital business models.

2 Experiences with using the acatech Industrie 4.0 Maturity Index in industry

Since its publication in 2017, the acatech Industrie 4.0 Maturity Index has been used by several companies to guide their digital transformation process. The fact that the STUDY has been downloaded ten thousand times from the websites of acatech and its project partners indicates just how widely it has been used. Feedback from manufacturing companies themselves and from the STUDY authors who have participated in their transformation projects has also provided deep insights into the use of the acatech Industrie 4.0 Maturity Index in industry. The following scenarios describe its main applications.

Digitalisation roadmap for individual manufacturing facilities

Initially, companies use the acatech Industrie 4.0 Maturity Index to establish their digital status quo. At this point, it is essential for a site's core processes to be investigated separately, since this makes it possible to build up a detailed picture of which areas have already attained a high digital maturity stage and where there is potential to do more. The results can be used to systematically identify the necessary measures and prioritise them using the maturity stage model. This approach helps to stop companies from initiating too many measures all at once, as well as ensuring that none of the key elements are overlooked.

Synchronisation of digitalisation activities throughout the company's facilities

By using this methodology across all of their facilities, companies can compare and synchronise their digital processes. The individual status quo analyses help to identify company-wide priorities that can be addressed synergistically through centrally delivered solutions. This prevents each site from coming up with different solutions for the same problem.

Global rollout and progress monitoring of the digitalisation strategy

Similarly to the previous scenario, companies also use the methodology to roll out their centrally formulated digitalisation strategy across their different sites. As with the introduction of new production systems, this is accomplished through a central

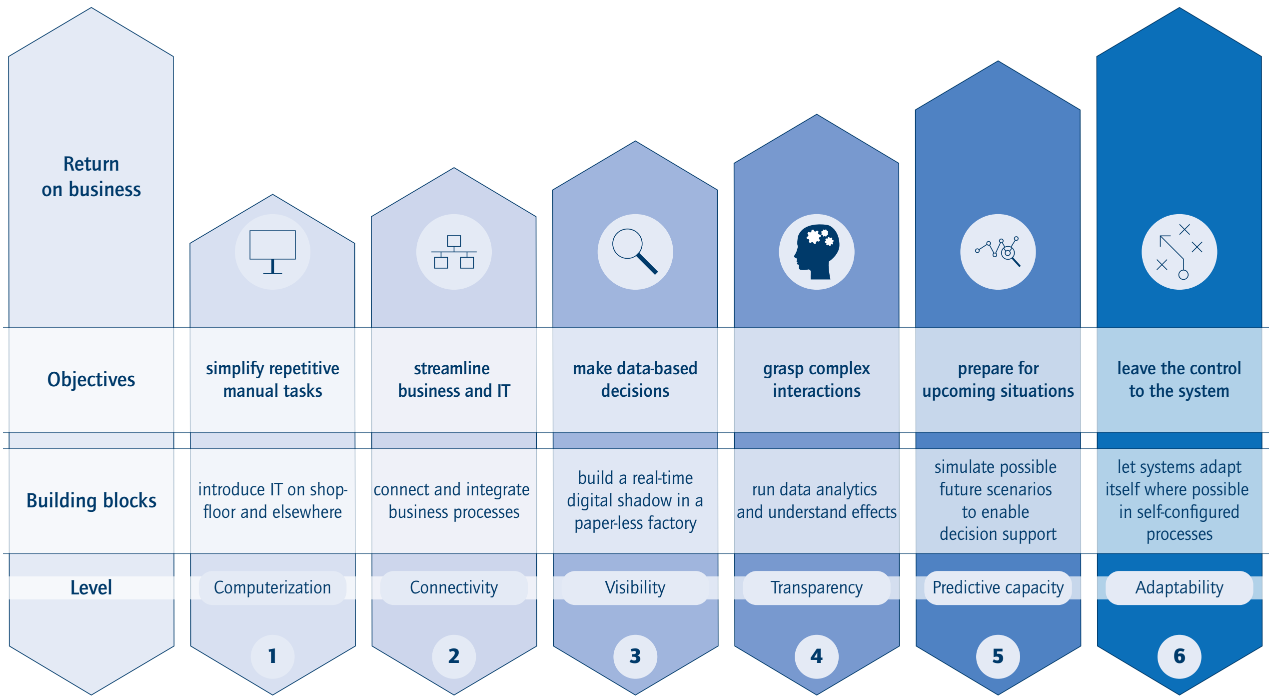


Figure 2: Maturity stages of the acatech Industrie 4.0 Maturity Index (source: Industrie 4.0 Maturity Center)

digitalisation organisation that employs internal experts to introduce the relevant standards and technical solutions at site level. The experts determine the site's digital status quo and draw up a digitalisation roadmap in conjunction with the local colleagues. The roadmap is subsequently used to monitor progress.

Technical due diligence for factories in the context of mergers and acquisitions

The methodology can also be used in a technical due diligence context. When carrying out due diligence for potential acquisitions, the Maturity Index can help to identify technical risks or previously unrecognised potential.

The methodology's two core principles are key to all of the above scenarios. The first of these principles is the prioritisation of projects on the basis of maturity stages (see Figure 2) in order to focus on the technological solutions that are most relevant to the company's current situation. The second involves focusing on the structural areas of resources, information systems, organisational structure and culture. These core principles help to ensure the effectiveness of the technologies that are deployed.

2.1 What progress have companies made so far?

The Industrie 4.0 Maturity Center in Aachen has carried out over seventy maturity stage studies (see Figure 3) of companies that are already using the Maturity Index. On average, the companies in question have already taken measures to enable the use of near real time data in the structural areas of culture and organisational structure (see Figure 3, maturity stage 3 "visibility"). What this means in practice is that the organisation regularly consults data and implements measures based on this data in its (day-to-day) operations. For example, shop floor meetings might be held at the start of each shift to discuss the indicators for the previous shift.

In the structural area of culture, the attainment of maturity stage 3 might mean that the business practises a philosophy of continuous improvement. The attainment of "visibility" in the areas of culture and organisational structure can be attributed to the fact that many companies have implemented lean management programmes in recent years.

There has been somewhat less progress in the areas of resources and information systems. Companies now mostly work with digital data and documents and these are also widely accessible throughout the organisation (maturity stage 2 "connectivity"). However, they have yet to achieve near real time aggregation and visualisation of data from different source systems (maturity stage 3 "visibility").

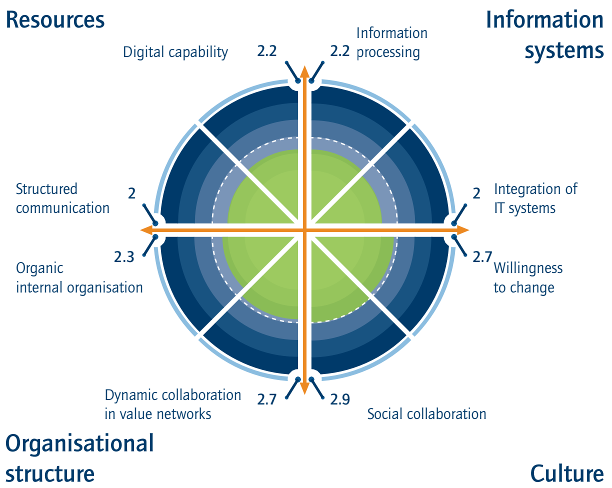


Figure 3: Average scores for the eight principles of the acatech Industrie 4.0 Maturity Index; n = 70 (source: Industrie 4.0 Maturity Center)

In terms of the companies' overall maturity stage, i.e. their average score for all eight principles, the majority are currently at maturity stage 2 "connectivity" (see Figure 4). 80% of the studied companies have already taken the first steps towards connecting their machines, systems and people. However, there is still a long way to go – none of the companies have yet attained maturity stage 4 "transparency" or higher, while a small proportion of companies (16%) are still starting out on their journey and have yet to move beyond maturity stage 1 "computerisation". To date, just 4% of the studied companies have attained an average maturity stage score of 3 ("visibility"). Since Industrie 4.0 is defined as beginning at the "visibility" stage, only a small proportion of companies can be said to have successfully accomplished digitalisation (maturity stages 1 and 2) and commenced the large-scale implementation of Industrie 4.0.

The companies can be divided into three overall categories based on their current progress towards implementing Industrie 4.0: the "laggards" who are still at the "computerisation" stage, the "beginners" who are at the "connectivity" stage, and the "leaders" whose average maturity score puts them at the "visibility" stage.

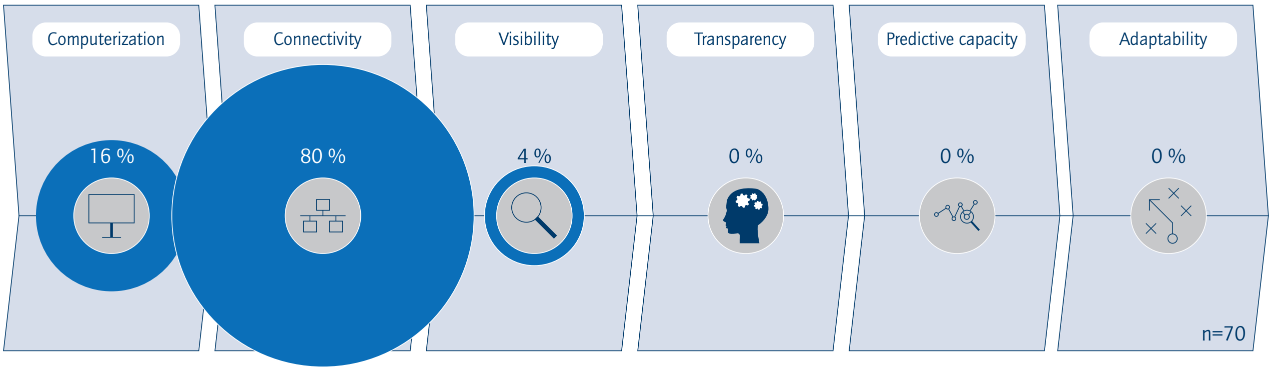


Figure 4: Companies by average overall maturity stage; n=70 (source: Industrie 4.0 Maturity Center)

Figure 5 shows the distribution of the maturity stages in all four structural areas (resources, information systems, organisational structure and culture) for the three categories of laggards, beginners and leaders. The maturity stage of the structural areas was plotted for each of the companies in these groups. Most of the companies in the laggards group have a maturity stage score of between 1.1 and 2 for the structural areas (blue box). However, it should be stressed that this group shows a wide spread of structural area maturity scores, ranging from 1 to 3.3 (lines either side of the blue box). A similarly wide distribution is evident in the beginners group. This significant variation in the maturity stage scores indicates that the four structural areas of resources, information systems, organisational structure and culture are not well coordinated. This failure to achieve consistent maturity stage scores across the individual structural areas means that one of the key success criteria of the Maturity Index has not been met. In the leaders group, on the other hand, the average scores are very similar to each other. Figure 5 shows a much smaller spread in the maturity stage scores for this group (2.6 to 3.7). The leaders have recognised the importance of this success factor and tried to attain a similar maturity stage across all the structural areas.

Figure 6 looks at the next level down, showing the average scores for the individual structural areas. The companies have already achieved a relatively high maturity stage in the areas of culture and organisational structure. In the structural area of "culture", 31% of companies have reached the "visibility" stage or higher ("transparency", "predictive capacity" or "adaptability"). In the area of "organisational structure", 86% of companies have at least reached the "connectivity" stage. The studied companies

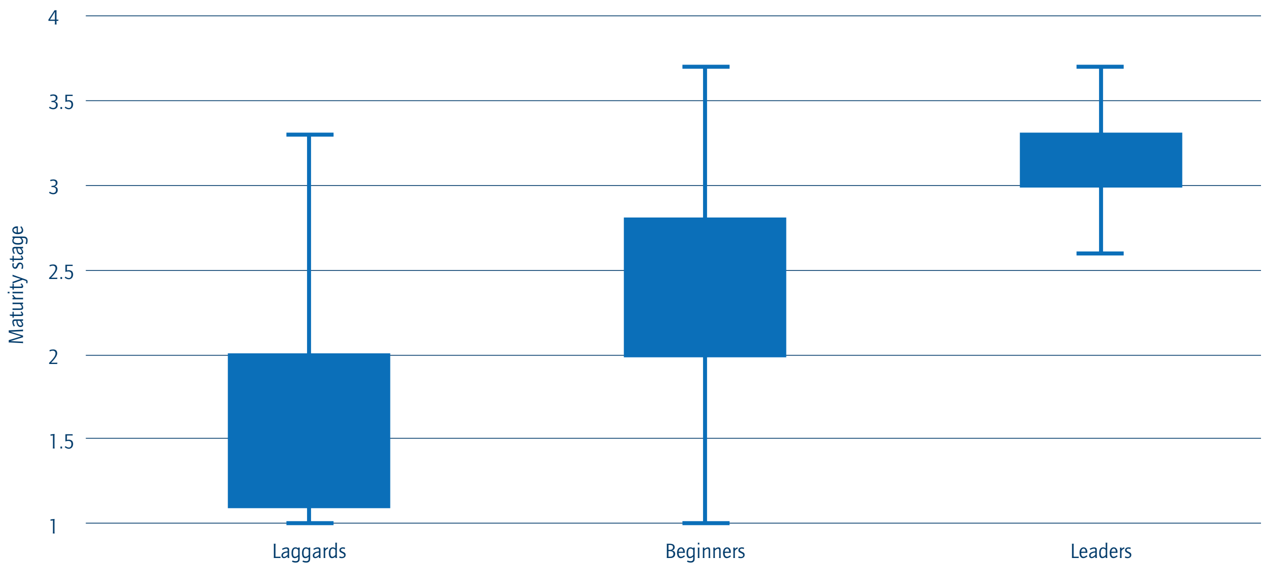


Figure 5: Distribution of overall maturity stages for the different company categories; n = 70 (source: Industrie 4.0 Maturity Center)

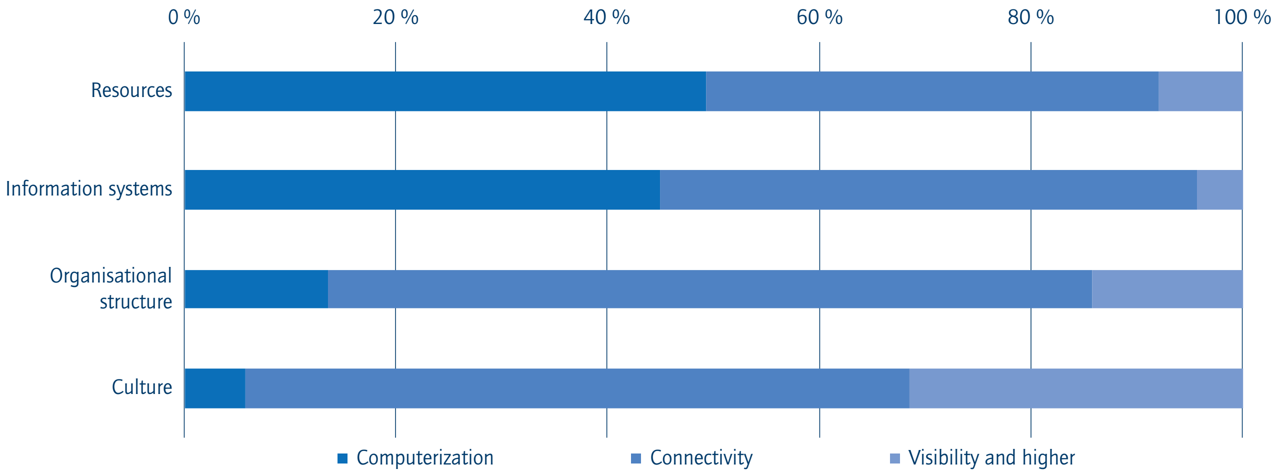


Figure 6: Distribution of companies' maturity stages for the four structural areas; n = 70 (source: Industrie 4.0 Maturity Center)

are thus making good progress in the structural areas of culture and organisational structure. However, both the statistics and the experience of acatech Industrie 4.0 Maturity Index users indicate that they still have a long way to go on the technological front. Just under half (49%) of companies using the Maturity Index are still at the "computerisation" stage in the structural area of "resources". This means that they have yet to achieve widespread "connectivity" of their machines and equipment. The picture is similar in the structural area of "information systems". 45% of companies have still not achieved extensive horizontal and vertical integration of their in-house systems.

2.2 The digital diseases afflicting companies

Many of the companies using the acatech Industrie 4.0 Maturity Index are affected by similar problems, the most obvious of which is that they tend to focus more on implementing isolated Industrie 4.0 prototypes and technology studies than on coherent, company-wide transformation programmes. This means that the necessary structural changes in the organisation and IT architecture are being neglected in favour of comparatively minor projects. Analysis of the Maturity Index's individual structural areas reveals that the same "digital diseases" keep cropping up time and again.

Structural area "resources"

The structural area of "resources" addresses machine connectivity, i.e. the extent to which different types of machinery are digitally connected to form a single system. The fact that many companies' structures have been built up over long periods of time is readily apparent in this area – over the years, these companies have failed to ensure common machine control standards when expanding or successively upgrading their plant. As a result, they now have an assortment of different protocols and data models. Connecting the controllers to newer systems is a job that can only be performed manually and often requires a retrofit. Both these operations call for qualified experts in control technology and OT-IT (Operation Technology and Information Technology) integration – two areas where experts are currently in short supply.

As well as machine controllers, auto-ID technologies (Radio Frequency Identification – RFID and QR codes) are also an important source of data. These technologies enable real-time data-based transparency throughout the entire order management process without the need for manual data collection. Besides capturing a variety of different indicators, auto-ID technologies also make it possible to record various operations and trigger additional processes. However, many companies are deterred from introducing RFID systems throughout the business by the investment costs. This is because they are not looking at the bigger picture – their calculations only consider the direct labour cost savings (e.g. for manual recording), and do not take account of the planning and management benefits of real-time data or the enhanced data quality.

Structural area "information systems"

The vision of Industrie 4.0 relies on fully integrated and automated information flows throughout a company and even

Interview with Mark Colwell and Mark Jaxion of Danish Vestas Wind Systems A/S

Vestas Wind Systems A/S, based in Aarhus, Denmark, is the world's largest manufacturer of wind turbines in terms of turnover and installed capacity (as of 2018). With more than 40 years in the wind industry, Vestas has installed more than 113 gigawatts of wind power capacity. Vestas turbines have been installed in 81 countries around the world, operating on every kind of site, from high altitude to extreme weather conditions.

Mark Colwell is Chief Engineer of product lifecycle management (PLM) at Vestas.

Mark Jaxion is Senior Specialist and Director of Vestas' IoT and Industry 4.0 Strategy.

What does digitalization mean for your business?
Mark Colwell: Our business is based on a global and highly distributed infrastructure, which is designed, manufactured, erected, and maintained by us. We have had our wind turbines and plants connected and streaming near real time data from around the globe for decades. We have learned a lot about data and information management from this experience and for the last few years we have been focused on connecting our design systems and operations systems together. Utilizing data and creating information is a huge opportunity for better decision making in the complex environment we work in.

How would you describe the business value you experience with Industrie 4.0?
Mark Jaxion: Our management is willing to invest in capabilities and basic infrastructure such as the digital connectivity of our systems and machines. Even if they do not necessarily return in the short term, these investments give us capabilities that will be important in the future. Of course, you always have to be business-case-driven, but instead of chasing high-flown business cases, we focus on using the aforementioned capabilities and infrastructure to enable sustainable value for the business. So we focus among other things on eliminating time to market, which doesn't necessarily end in a reduction in cost, but does significantly strengthen our competitive advantage.

What do you consider the greatest obstacles to successful digitalization and how do you overcome them?
Mark Colwell: Use cases cannot be brought into the organization top down. It is important to talk to the people who will be most affected, i.e. on the shopfloor and in the field. The people have to be willing to trust the system and the decisions or suggestions it makes. Therefore, they have to be integrated into the search and development of use cases.
Mark Jaxion: One word: Master Data. In all our efforts to learn from data it comes down to legacy data. For instance, augmented reality is not possible for wind turbines we erected in the 80s. We don't have the CAD data. Taking the physical world into the digital world is much more difficult than vice versa. That is the major challenge and requires a lot of basic work and effort.

What would you like to share with others who are on their way to Industrie 4.0?
Mark Colwell: You should look at your ambition: what do you want to achieve in the short and medium term? This should be evaluated against the foundation of what is already there: what is possible and where do you actually need to improve? A long-term vision and roadmap taking the companies' strategic goals into account is essential.
Mark Jaxion: Implementing Industrie 4.0 is not just an application of technology, it means changing the skill set within management, on the shopfloor and in the field. You should focus on capabilities as enablers and not just on technologies. They are just a tool.

between the company and the outside world. Human intervention is no longer necessary at any point from the generation of the raw data by the sensors to its aggregation, analysis and presentation. Two main problems are apparent in this area:

1. While integration of different systems is occurring, it is very fragile. Many companies have a variety of home-grown solutions, databases and tables that support data collection and processing by their employees. The Excel sheet used for detailed day-to-day production order planning is a typical example – every day, this sheet is exported from the Enterprise Resource Planning (ERP) system and updated by the shift supervisor. Feedback about the order is input manually by the shift supervisor or in some cases directly by the machine operators. While the operators do often have access to a system with rudimentary Manufacturing Execution System (MES)

functionality, it does not usually allow for the bi-directional exchange of data with the ERP system or the machine controllers. In other words, despite the use of IT systems, a lot of data and information is still recorded and shared manually. As well as higher personnel costs, this means that real-time data is not available.

2. The quality of the data, particularly the master data, is not good enough. For example, although operating and test instructions are available digitally as PDFs or worksheets, they are not standardised, have not been assigned to the relevant master data and are scattered across the company's different file servers. The upshot is that although there are no technical obstacles to the factory introducing new systems such as a modern MES, a huge amount of work is required to cleanse the master data.

Structural area "organisational structure"

Many manufacturing companies still have hierarchical organisational structures based on functional areas, with correspondingly structured target systems for management. As a result, there is little incentive for different parts of the business to cooperate with each other. However, interdepartmental collaboration is essential for many digital transformation projects. While certain data may be of no direct value to the department where it was generated, it could well have a valuable use in another department. For instance, the data from the design department's highly detailed CAD models can be of use during the rest of the product's life cycle and for maintenance purposes.

Structural area "culture"

One weakness shared by many companies in the area of "culture" is that there is no or not enough active employee involvement in the change projects that affect them. For example, new IT systems are almost always chosen exclusively by the IT department. This can lead to resistance in the departments that will be using them and low acceptance of the systems in question. More modern approaches recognise that a system's requirements should primarily be defined by its users who should therefore be involved in choosing and implementing it.

Raising awareness of the importance of data quality is another challenge. Employees often don't realise the consequences of errors in the creation of master data, or the benefits of carefully documenting faults and their solutions.

2.3 Areas requiring urgent action by companies

The use of the Industrie 4.0 Maturity Index in industry has clearly highlighted the challenges for companies and the areas where urgent action is required. In the next section, these are described in detail for the four structural areas of resources, information systems, organisational structure and culture, providing a basis for the subsequent formulation of roadmaps for the different stages of the digital transformation.

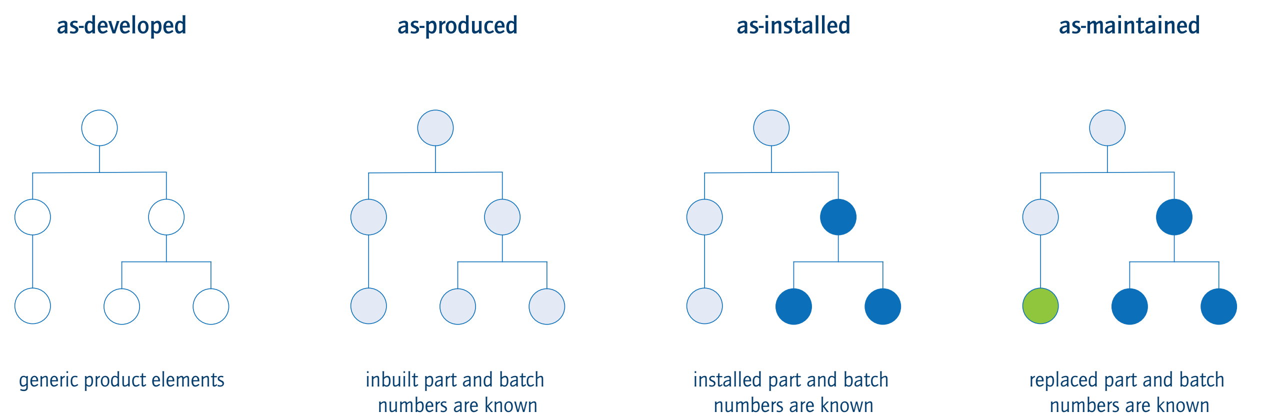


Figure 7: Components as information carriers throughout the product life cycle (source: Industrie 4.0 Maturity Center/TU Darmstadt)

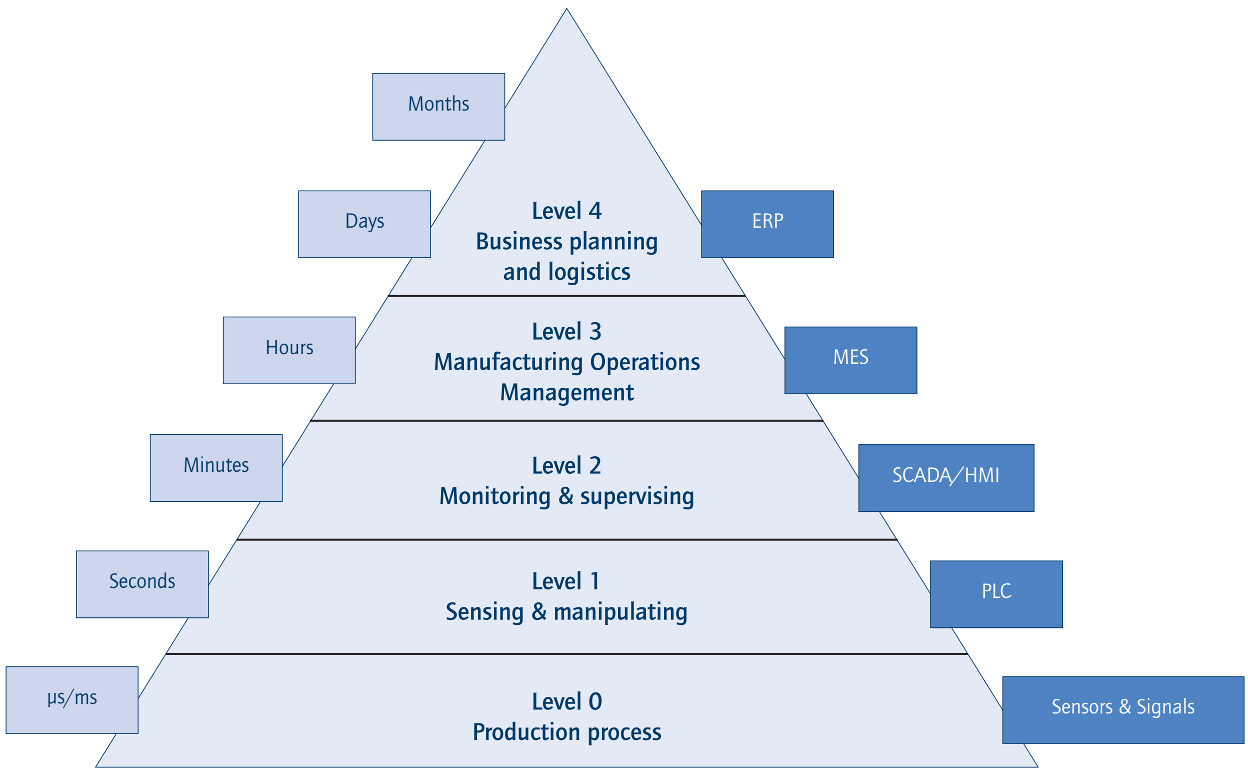


Figure 8: Automation pyramid based on the ISA 95 model (source: Åkerman 2018, p. 2)

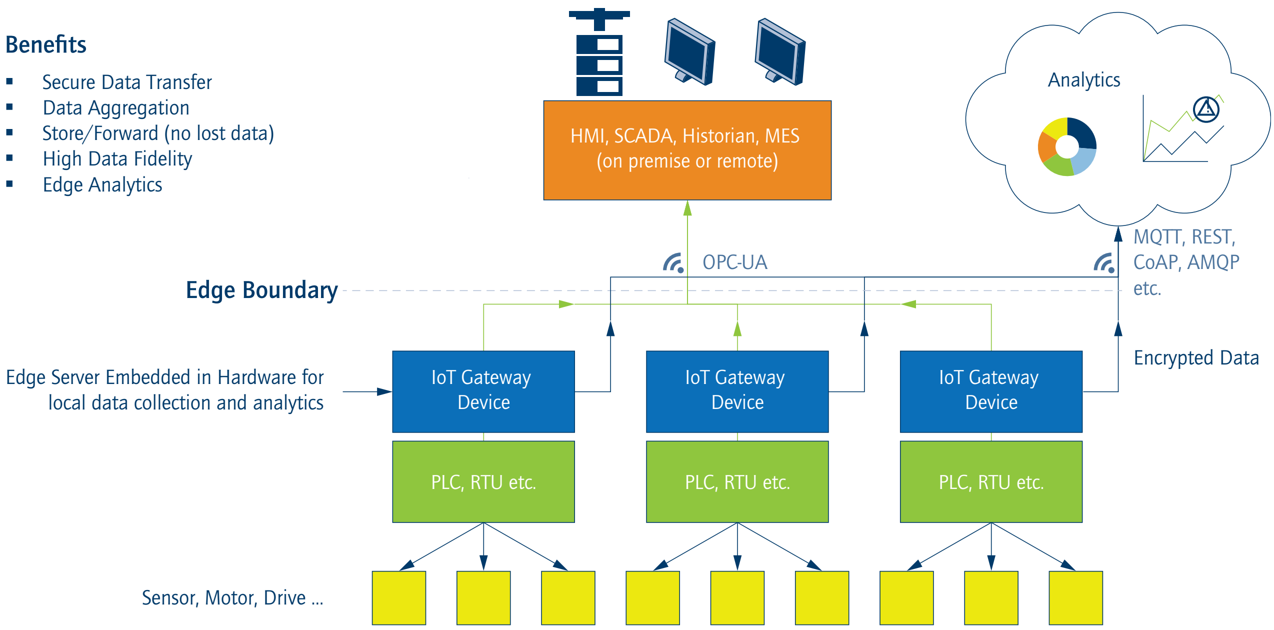


Figure 9: Combination of edge and cloud computing for data aggregation and analytics (source: PTC)

2.3.1 Individual parts of products as information carriers

End-to-end data delivery throughout the entire value chain must include the manufactured product. This means that the product's individual parts – made up of modules and individual components – are just as important. Accordingly, we recommend the adoption of the "components as information carriers" approach, in which information about components is collected and combined throughout the entire product life cycle, from development and production right through to the usage phase.

Applications include the creation of bills of materials (see Figure 7). Throughout the entire product life of a machine or piece of equipment, a product data model can be used to store information about the properties of its parts. The product data model, which describes the design properties and values, can be augmented with the actual physical properties and values of each manufactured component. This approach makes it possible to combine information from different production data sources in order to generate part-specific information that can be used to add value across every life cycle stage. The components become information carriers, since they collect information about themselves throughout their entire life cycle.[1] The company uses solutions such as Product Lifecycle Management (PLM) systems in order to manage this key challenge of collecting the relevant data, processing the resulting information and combining it to add value.

2.3.2 Replacing automation pyramids with edge and cloud computing

Many companies use the automation pyramid as a model for their IT architectures (see Figure 8). However, the progressive introduction of digitalisation technologies in the shape of cloud and edge computing is now breaking down hierarchical IT system architectures.[2] The networked physical platforms and software-defined platforms described in the Smart Service Welt[3] layer model are particularly key in this regard. The large software companies are migrating from the public cloud to an edge computing approach to production optimisation and management. Capacity is being moved from data centres (cloud computing) to local networks (edge computing) in order to better address requirements relating to responsiveness, autonomy and data protection, including the protection of production know-how.[4] Edge computing involves the use of smaller, decentralised, on-premises data centres capable of the local aggregation and analysis of data from very different sources (see Figure 9). While complex applications can still mostly be carried out in the cloud, pre-processing takes place in the edge environment. Various combinations of cloud and edge computing are becoming more and more common in industry, with businesses and cloud providers increasingly pooling their know-how and forming partnerships in order to implement these architectures. One example launched last year is the partnership between Volkswagen, Amazon and Siemens, which aims to deliver significant material flow and logistics optimisation by connecting equipment, factories and – in the future – also suppliers in the Volkswagen Industrial Cloud. The GAIA-X concept is also based on central technical requirements for the architecture of a federated, open data infrastructure, for example on decentralised or distributed data processing via multi-edge, multi-cloud or edge-to-cloud processing. This data infrastructure aims to guarantee the trustworthiness and sovereignty of users and their data.[5]

2.3.3 Practical example of agile work organisation: 72-hour prototyping

Until recently, most agile organisations were found in the IT, services and marketing industries. However, a family business that uses modern management techniques has shown how it is possible to create an agile organisation in manufacturing industry, too. This agile organisation was introduced in parallel to the functional, hierarchical manufacturing organisation. It all began with a hackathon, where staff at BEULCO GmbH & Co. KG[6,7] (hereafter Beulco) were given 72 hours to develop a smart prototype for a product outside of their usual product spectrum. But this was just the start of the company's transformation into an agile organisation. To drive the transformation process, twenty "CoPs" (Communities of Practice) were formed from the company's 180 employees. These were the in-house points of contact for transformation projects and were also responsible for their orchestration (moderation, coordination and documentation). In addition to two CoPs per project, there are also "theme owners" who take on responsibility for the development of a project or project idea. Employees join whichever project they are interested in, developing and implementing it together with the theme owner. Rather

1 | See Anderl 2015, pp. 753–765.
2 | See Verein Deutscher Ingenieure e. V. 2013.
3 | See Arbeitskreis Smart Service Welt/acatech 2015.
4 | See Willner 2019.
5 | See BMWi 2019a.
6 | BEULCO produces water supply systems and solutions, especially for the domestic connection and mobile water supply markets.
7 | BEULCO was the winner of the 2019 Digital Champions Award in the "SME Transformation" category.

than the theme owner being solely responsible for the project, responsibility is shared between the whole project team.

Employees are given time off and a room to work on their projects. There is also a pinboard where any employee can post new ideas for transformation projects. If the idea is deemed to be worth pursuing following discussion with one of the CoPs, the employee becomes the project's theme owner.

When it comes to initiating projects, the company's management adheres to the agile methodology. This means that they cannot start a project themselves – a bottom-up approach is employed where projects must be initiated by the workforce.

2.3.4 Empowering staff to shape the transformation

When building an agile organisation, the key to a successful digital transformation is not just to involve staff but to empower them to shape the transformation processes (see 2.3.3). For example, it is important to identify and train a diverse mix of change catalysts across all levels of the company hierarchy (e.g. CoPs, see 2.3.3). These are the people who will orchestrate the digital transformation and ensure that genuine change is achieved. Importantly, shop floor workers who take on this role must also be empowered to shape the digital transformation on an equal footing with other members of the company.

This bottom-up approach where the transformation process is handed over to the workforce calls for a mindshift on behalf of management, since it involves relinquishing control of project planning and management. In other words, the hierarchical structures typically found in manufacturing companies must be broken down. Thus, as well as providing management with initial and ongoing in-house training in modern leadership methods, it should be recognised that the transformation process is also a matter of their individual personal development.

Just as management must learn to hand over responsibility, the workforce must grow accustomed to having more responsibility. Agile organisations rely on engaged employees who take on more individual responsibility across every level of the company hierarchy. Staff take the lead on everything from proposing ideas to initiating and carrying out projects. Importantly, no-one is compelled to participate or take on more responsibility – doing so is always entirely voluntary. This ensures that the employees who come on board are motivated to make change happen and passionate about the subject in question.

3 Case studies

3.1 Using the acatech Industrie 4.0 Maturity Index in companies

Published in 2017, the first edition of the acatech STUDY Industrie 4.0 Maturity Index aimed to develop a standard tool for guiding manufacturing companies through their digital transformation. The goal was to provide companies with immediate support in developing a strategy that could then be directly executed. Rather than simply launching a few initial pilot projects, this would allow them to implement a structured and efficient transformation process. Three years on from its publication, the STUDY must now be judged against this goal.

Over the past three years, the Index has been used by several companies across a range of different industries – in other words, its use has not been confined to discrete manufacturing. For instance, the Index supported the digital transformation of a German chocolate manufacturer, where it helped to identify potential productivity gains in the production of high-quality chocolate products. While in this case, the Industrie 4.0 Maturity Index was only employed within the company itself, synergies are created when it is applied across an entire value chain.

In the following sections, we present case studies of four different companies. As a company with over 230 sites worldwide, the main challenge for ZF Friedrichshafen AG was to ensure that the Index was used in a standardised manner (see 3.2). The HARTING Technology Group was one of the first companies to use the Industrie 4.0 Maturity Index in practice, as already described in the 2017 acatech STUDY. Based on the findings of the status quo analysis carried out at the time and on the subsequently formulated roadmap, HARTING created an interdisciplinary Industrie 4.0 task force that was charged with implementing the transformation and has successfully carried out a number of initial projects (see 3.3). The production chain of Kuraray Europe GmbH (see 3.4) comprises three separate facilities. This case study provides an impressive illustration of the synergies that can be achieved by analysing the production chain and formulating a joint roadmap. Finally, the case study of a chocolate factory (see 3.5) focuses on how the Index can be used to increase efficiency and output in the food industry.

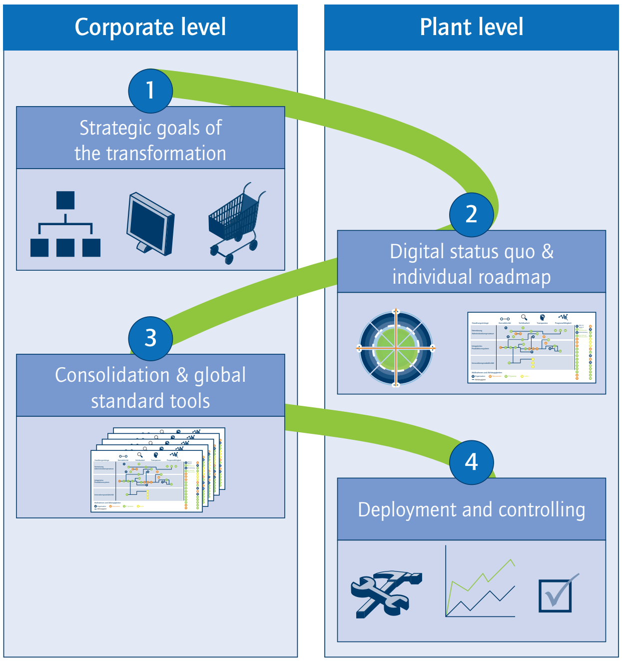


Figure 10: Digital transformation strategy at ZF (source: Industrie 4.0 Maturity Center and ZF Friedrichshafen AG)

3.2 ZF Friedrichshafen AG: Industrie 4.0 rollout across 230 sites

The implementation of Industrie 4.0, digitalisation of the manufacturing value chain and the use of artificial intelligence can create opportunities for cost and efficiency optimisation, enhanced profitability and the development and implementation of innovative new business models. At the same time, however, it also entails radical and dynamic changes to the business environment, structural changes in value networks and high investment costs. These are the challenges facing ZF Friedrichshafen AG (ZF), a leading global technology company based in Friedrichshafen, Germany. ZF has several divisions, each with various business units that develop different products and pursue different strategic objectives. Since the company has over 230 sites, precise planning of the digital transformation in the different parts of the business is essential. In a global company like ZF, even though the sites that make up the business units can have a similar structure, they have often evolved differently over time, which can make it difficult to compare them at a global level. A four-stage digital strategy was employed in order to ensure that both the overall group-level strategy and the individual site-level issues were addressed.

The first step was to define the strategic goals at the group level. The status quo of each individual site was then determined and the results used to produce a site roadmap. Finally, all the results from the individual sites were consolidated into a global roadmap. Implementation was supported by centrally provided technologies (see Figure 10).

ZF established an Industrie 4.0 system house at group level in order to develop and supply group-wide standards and solutions e.g. for strategic production management systems, device connectivity and IT security in production. In order to realise the digital transformation, it was necessary to strike a balance between a central strategy for leveraging synergies and individual changes at the business unit and site levels. The Industrie 4.0 system house is the central organisation tasked with performing this function. It facilitates best practice sharing, is responsible for the deployment of task forces and creates a common framework that provides a standard structure for transformation activities both within and across individual sites.

While ZF had already started to develop the Systemhouse Industrie 4.0 at group level, the company lacked a standardised tool for objectively measuring the status quo in the individual plants and feeding the results into a digitalisation strategy. The existing ZF Production System provided a model for the introduction of such a tool across the entire organisation. In the ZF Production System, employees are locally responsible for lean management, but organisational structure and standardisation are managed centrally. The acatech Industrie 4.0 Maturity Index was chosen as the standardised digital transformation tool and has now been incorporated into the Industrie 4.0 system house. Among the reasons for choosing the acatech Index was the objectivity provided by the questionnaire and standardised procedure. The Index also incorporates organisational and cultural aspects, enabling seamless integration with lean management activities. Moreover, ZF wanted a tool that its own employees would be able to use objectively, so that all sites could be included in the digital transformation after an initial pilot phase.

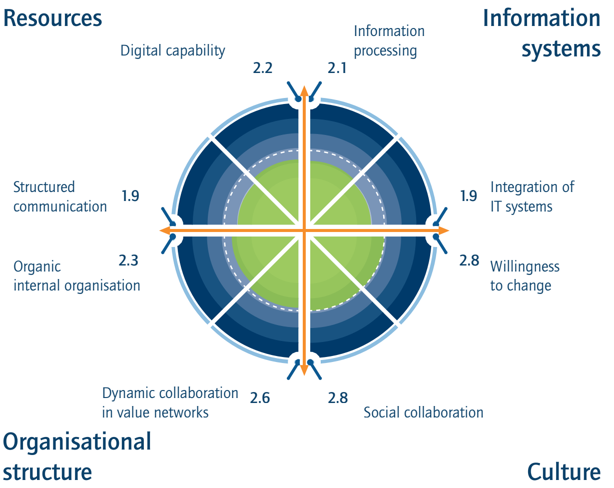


Figure 11: Example of status quo scores for a ZF site (source: ZF Friedrichshafen AG and Industrie 4.0 Maturity Center)

During the initial pilot phase, ZF used the acatech Industrie 4.0 Maturity Index to analyse processes such as production, logistics, quality and planning at 14 facilities in 10 countries spread across Europe, Asia and North America. Supported by staff from the Industrie 4.0 Maturity Center, each facility carried out a maturity stage study to establish its status quo, focusing on the site's core processes (see Figure 11). The results of the status quo analyses revealed that although the details vary from one site to another, they have a number of key issues in common. For instance, almost all the sites were stronger in the areas of culture and dynamic cooperation throughout the value network than in the structural areas of information systems and resources. There were few differences between the individual sites' internal processes (planning & management, manufacturing & assembly, logistics & warehousing, engineering & maintenance, quality). This indicates that the implementation of Industrie 4.0 has been relatively consistent across the different parts of the business, with the result that the different sites have achieved a similar degree of progress for the individual processes.

The next step was to draw up individual roadmaps for each site based on the results of the local status quo analysis. As illustrated in Figure 12, these roadmaps systematically set out the measures required to achieve a higher maturity stage in the different areas of the business. As well as ensuring a uniform rate of progress across the different principles, this systematic approach minimises the risks associated with the implementation of the digital transformation as a whole. A group-wide roadmap was drawn up incorporating the areas of planning & management, manufacturing & assembly, logistics & warehousing, engineering & maintenance, quality and global levels. Up to five measures were identified for each area, and detailed profiles were produced for all of the measures proposed in the roadmap, including detailed descriptions of the costs and benefits, profit contribution, structural area and maturity stage in the Industrie 4.0 Maturity Index, and the affected processes.

In order to create synergies throughout the company, the changes must go beyond the level of the individual site. Consequently, when identical or similar measures are identified, the site roadmaps are consolidated to create a divisional or group-level standard. Examples of standardised digital solutions include software, devices and sensors that are offered and supplied centrally through a kind of app store. The different business units and sites can select the standard solutions that they wish to implement and adapt them to their individual requirements.

Following the initial pilot phase, employees from the different divisions were chosen to receive targeted, detailed training in the use of the methodology so that they could subsequently carry out projects themselves. In this way, each division built up a pool of experts with the know-how to support the ongoing digital transformation.

A local digitalisation manager is appointed for each site with local responsibility for the effective implementation of the digital transformation. In addition to the establishment of central services, a growing number of internal experts are being trained to manage the digital transformation. As with the existing lean management structure, networking between the digitalisation managers in different parts of the group results in the exchange of ideas and solutions between different sites. Wherever possible,

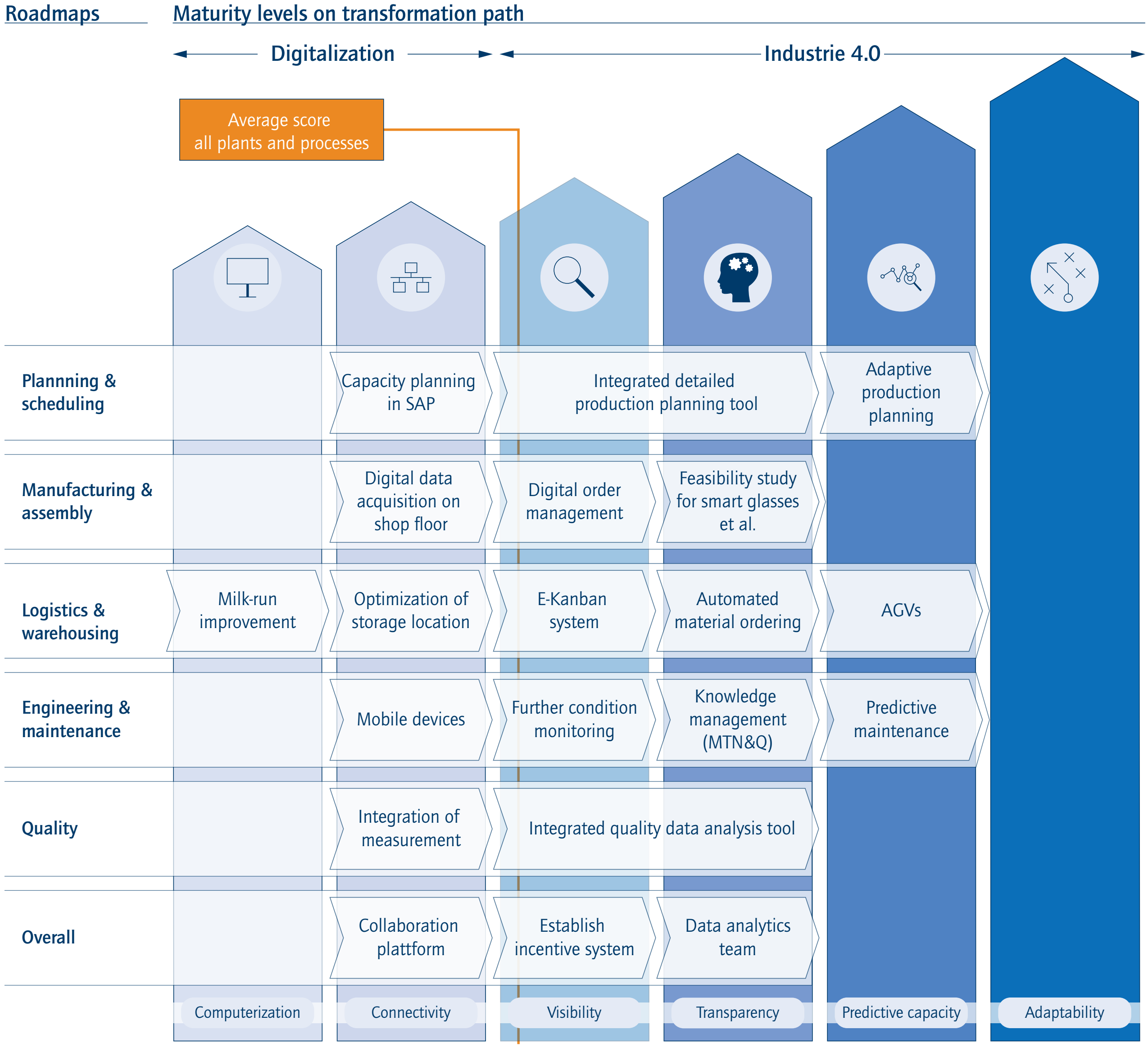


Figure 12: Example of ZF digital transformation roadmap including implementation measures (source: ZF Friedrichshafen AG and Industrie 4.0 Maturity Center)

standard tools are used throughout the group and agile working methods are employed to implement the projects.

In order to monitor developments at the individual sites and ensure that they are aligned with the corporate strategy, the status quo analyses are compared against each other and repeated on a regular basis if necessary. Ongoing monitoring of measures that have already been implemented and validation of new measures make it possible to respond flexibly to any changes. This ensures that the measures make an efficient contribution to the digital transformation of the global group.

3.3 HARTING Stiftung & Co. KG: using the Industrie 4.0 Maturity Index as the starting point for an integrated strategy

The HARTING Technology Group is a leading manufacturer of industrial connectors, device connection technology, ready-made system cabling and network components. With over 5,300 employees at 14 production facilities, HARTING meets the EU definition of a large enterprise. However, its structures more closely resemble those of a medium-sized enterprise. The company's headquarters and largest manufacturing facility are located in the town of Espelkamp in east Westphalia. In addition to its production sites in Germany, HARTING also has manufacturing facilities in China, Romania and the USA. As well as connector technology, the company's product portfolio includes information technologies such as RFID (Radio Frequency Identification).

As a member of the it's OWL cluster, HARTING was already involved in the first edition of the acatech STUDY "Industrie 4.0 Maturity Index". It was in this capacity that HARTING became one of the first companies to validate the acatech Industrie 4.0 Maturity Index in early August 2016. The key findings, which were published in the original 2017 STUDY, showed that by this point in time HARTING had on average already attained the "visibility" stage (see Figure 13). The upgrading of the company's IT infrastructure over the previous years and the systematic capture of manufacturing process data made it possible to create a digital model of the production environment in the company's information systems, providing a basis for subsequent initiatives. Even in 2016, HARTING had already done a lot of work in the field of Industrie 4.0, especially in its manufacturing facilities. As a result, the relevant departments were receptive to the deployment of further digital technologies. While the implementation of various pilot projects did lead to local process improvements, these were often isolated and fragmented, since their potential was not leveraged across all of the production lines.

As a result, the company decided internally that the validation of the Industrie 4.0 Maturity Index should serve as the starting point for the rollout of an integrated digitalisation strategy. A 2016 board resolution set out the key pillars of the transformation process:

- **Local focus:** Initially, the digital transformation should focus on the two manufacturing facilities at Espelkamp. Espelkamp is the company's largest manufacturing location, and the fact that the decision-makers, development team and IT department are also nearby is key to the success of the digital transformation.
- **Building in-house expertise:** External experts such as the Industrie 4.0 Maturity Center in Aachen can make a valuable contribution as network partners and as a source of ideas. However, the company wishes to focus on building its own expertise in this area in order to facilitate the programme's subsequent rollout at other sites around the world. In addition to technical expertise in a number of different disciplines, this will also call for expertise in the agile project management methods needed to implement the digital transformation.

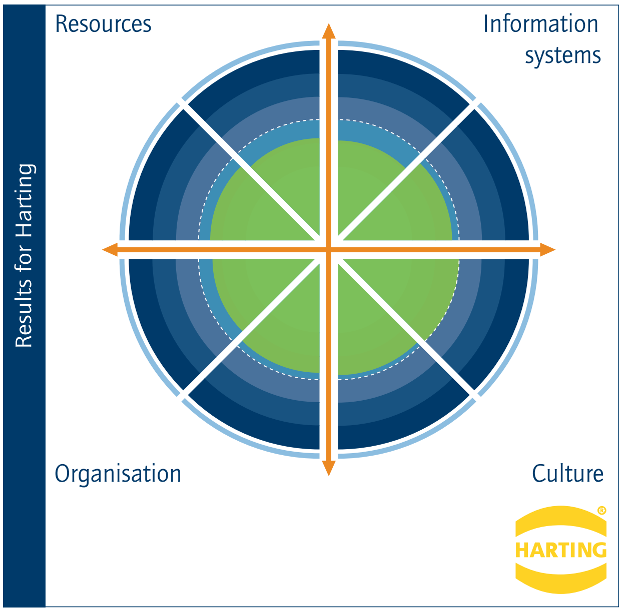


Figure 13: Example of the status quo scores for a HARTING site (source: acatech Industrie 4.0 Maturity Index 2020)

- **Goals:** The digital transformation must form part of the overall corporate strategy and its success should be reflected in the company's production figures. The ultimate goal of the transformation process is to attain the sixth maturity stage of "adaptability". An agile approach is key to delivering this goal, and it is important that the first quantifiable successes should be achieved while the project is running. Moreover, once the pilot stage has been completed, the focus should be on the entire value creation process in order to ensure that the potential benefits are fully leveraged.

Following on from this board resolution and the presentation of the results (status quo and roadmap) by the Industrie 4.0 Maturity Center, a workshop was held in order to fine-tune the priority of the individual roadmap elements and select the first projects. Since building commitment towards the digital transformation and embedding it within the organisation were among the key goals, the workshop's participants included the board member responsible for production, the Espelkamp plant managers and the managers of the centres of competence for the individual production departments. Given the focus on the Espelkamp site and the ultimate goal of achieving maturity stage 6, the name chosen for the project was "Digital Machinery Integration Espelkamp" (DIME).

To realise the project, a core team was established that was led by an Industrie 4.0 team manager based at HARTING's head office and included experts from the domains of industrial engineering, maintenance, quality management, sensor technology, automation and IT/software development. The involvement of all the relevant disciplines was key to the transformation's successful implementation. The team was supported by the central project management function, which supplied methodologies for managing and structuring the projects. In order to ensure rapid progress, the decision was taken to employ an agile project management approach with weekly sprints. The projects are broken down into individual component parts, each of which corresponds to a backlog task. These are then addressed by the relevant experts based on their priority and ease of implementation. A project steering committee coordinates the project work with the board member responsible for production, the plant manager and other internal stakeholders.

Figure 14: HARTING dashboard (source: HARTING Technology Group)

In order to enable the rest of the transformation, it was important to begin by integrating the production machinery via standard, state-of-the-art interfaces. The interfaces were piloted in the injection moulding part of the business. As well as integrating the machinery, additional data was captured as required by external sensors. In parallel, the company developed a powerful IT infrastructure capable of processing large data sets and of using future cloud services to analyse this data. In order to ensure that the solution is both efficient and cost-effective, a distinction was drawn between "hot" data streams that require urgent processing and less urgent "cold" data streams.

The goal of integrating the machinery and incorporating additional data is to simplify production system management by providing staff with information to support their decision-making. To this end, dashboards have been developed that give machine operators advance warning of when a job is about to be completed or a job changeover is imminent, as well as displaying the next set-up procedure and alerting the operators to potential faults (see Figure 14). In addition to providing shop floor workers with direct information via dashboards, integrating the machinery also makes it possible to automatically send setting data to the machines from the ME system. Digital fault type recording during routine production checks helps to build a further pool of knowledge that can be exploited digitally.

A company the size of HARTING obviously needs more than three years to complete its digital transformation. The collected data will continue to be analysed in order to identify ways of optimising production and help the company progress from its current maturity stage of 4 towards maturity stages 5 and 6. Nevertheless, leveraging any initial potential as quickly as possible is key to a successful transformation process. In the last three years, HARTING has increased both its productivity and its turnover – and in both cases this is at least partly attributable to the ongoing digitalisation of the production environment. The speed with which the relevant measures are implemented is also important to the Industrie 4.0 team manager. The rapid and structured production of a roadmap enabled by the Industrie 4.0 Maturity Index meant that the first measures could be taken swiftly, and also reduced the danger of basic elements being omitted. As well as the ease of implementation and concrete results, another important aspect is cooperation with the internal IT function on issues such as IT security, a standardised data model, the use of common tools and the development of a shared understanding of the goals. The company's decision to build its own in-house expertise has also paid dividends. The core team has developed an in-depth understanding of the subject matter and is now well placed to roll out the initiative to other production areas. At the same time, collaboration with the Industrie 4.0 Maturity Center allowed HARTING to learn from other companies' best practices. Although there has not yet been a second status quo analysis, the experts from the Industrie 4.0 Maturity Center have certified that the company's maturity level has increased since the first analysis.

3.4 Kuraray Co Ltd.: increasing overall equipment effectiveness

Headquartered in Tokyo, Kuraray Co Ltd. (hereafter "Kuraray") is a global specialty chemicals manufacturer with over 10,000 employees. The company is one of the largest suppliers of polymers and synthetic microfibres and an international leader in the development and use of innovative high-performance materials. Its products are used in laminated safety glass applications in the architecture, automotive and photovoltaic sectors. The company's product portfolio also includes chemical specialities, activated carbon filters, thermoplastic elastomers, manmade fibres, artificial leather and dental products.

Kuraray's three sites in Germany form a production chain for products such as laminated safety glass interlayers. The facilities have to cooperate and communicate with each other, since their processes constitute successive stages in the production chain, with intermediate products being transferred from one site to another. This structure where each of the three sites is responsible for different production stages poses challenges for the company in terms of coordinating planning for the German business as a whole. All the facilities make different products and have their own product-specific processes and different priorities. As is the norm in the chemicals and process industry, the plants are designed to have a long operating life, and have a complex structure that makes any work to upgrade them extremely time-consuming. In addition, all the plants operate 24/7, further complicating the implementation of new (IT) systems. Yet the introduction of these new systems is key to ensuring a continuous, automated information flow. A structured, carefully planned approach is paramount, since the implementation of new systems and upgrading of existing ones will inevitably be a lengthy process necessitating the scheduling of downtime. Moreover, given the materials made in the chemicals and process industry, IT security is particularly critical. Prevention of unauthorised access to data or production equipment is a top priority. This complicates the implementation of new systems within the individual production facilities and is also an obstacle to connectivity between the three sites. Yet the

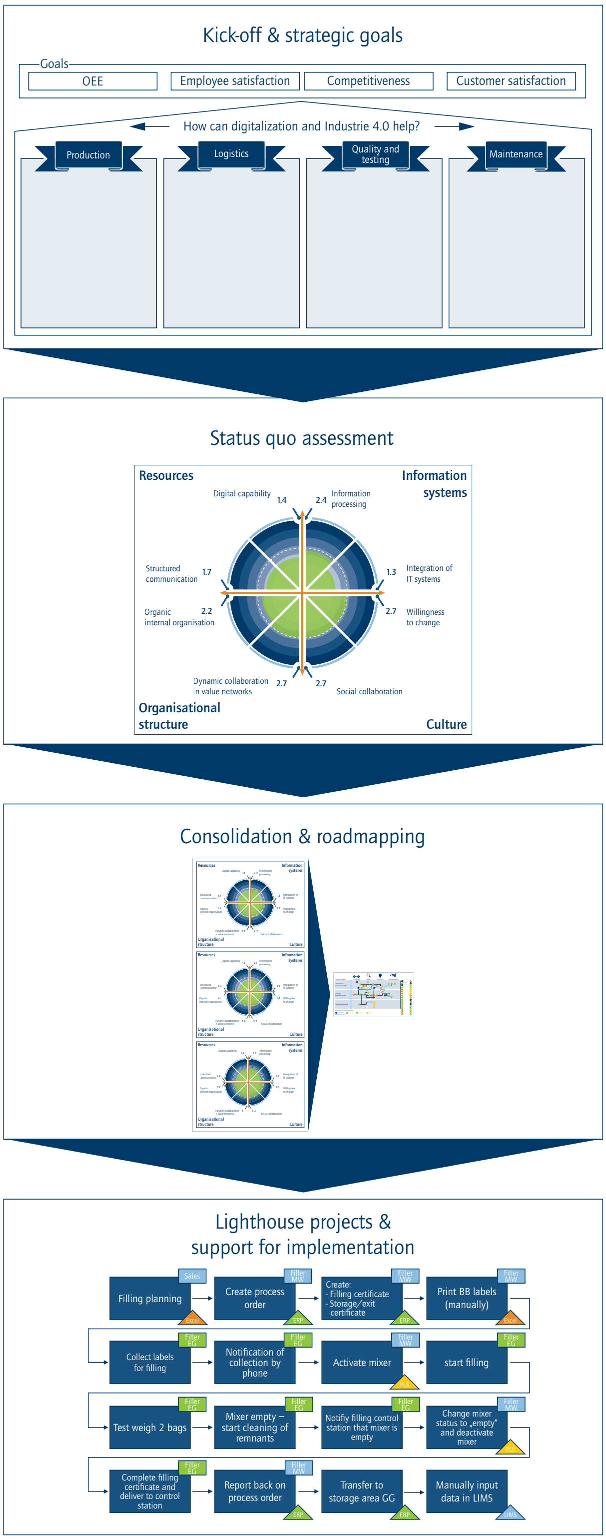


Figure 15: Digital transformation strategy at Kuraray (source: Kuraray Co Ltd. and Industrie 4.0 Maturity Center)

fact that materials and intermediate products are supplied by one site to another makes it particularly important to simplify the system for exchanging information between facilities. It is clear from the above that the implementation of the digital transformation at Kuraray called for a structured approach within a sound methodological framework. This is where the acatech Industrie 4.0 Maturity Index came in.

At the outset of the project, Kuraray set itself three goals. Firstly, it wanted to increase overall equipment effectiveness (OEE). This includes both the prevention of downtime and the realisation of productivity gains through process improvements. Another OEE priority is to achieve a transparent material flow for all (intermediate) products in order to ensure a transparent basis for data-based decisions. Secondly, iterative product development steps and short time-to-market cycles were established in order to speed up the product improvement process. Last but not least, the company also wanted to improve operational and occupational safety. This third goal included learning from incidents and active change management. It was made clear that the above goals must apply to all three sites.

A digitalisation project was launched in order to deliver these goals and drive the digital transformation at Kuraray. The project implementation was led by colleagues from the Industrie 4.0 Maturity Center in Aachen. The project encompassed i. a. the formulation of the digitalisation goals, the on-site phase including the status quo assessment at the different production facilities, and the analysis phase leading to the production of a digitalisation roadmap (see Figure 16). The focus was on the capabilities that the Index outlines for the four structural areas, which are broken down across the six maturity stages. The first step involved formulating and stipulating the common goals for all three sites. This was followed by the on-site phase, in which the status quo of all the relevant KPIs, processes and information flows was determined. This assessment was based on the Industrie 4.0 Maturity Index's four structural areas of resources, information systems, organisational structure and culture. The results showed that Kuraray was already very strong in the structural areas of organisational structure and culture. There was a clear determination to take the necessary steps to become a digital business, and the initial foundations had already been laid. For instance, lean management methods had already been implemented together with a continuous improvement process for optimising operating procedures. However, the findings for these areas also revealed that there was no standardised approach to project prioritisation and planning, and that the exchange of information and materials between the sites was only optimised locally. A number

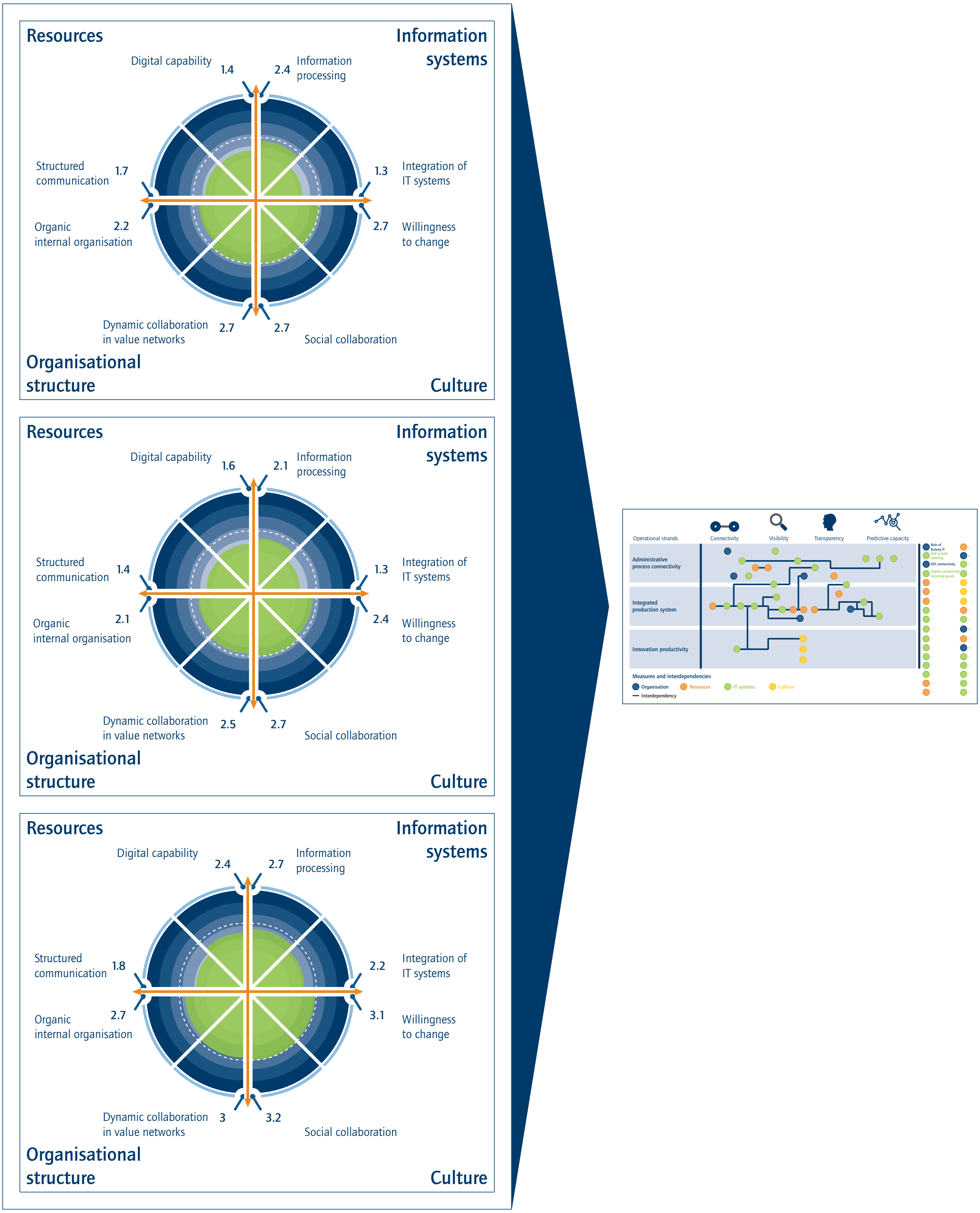


Figure 16: Status quo assessment of all sites and consolidated roadmap (source: Kuraray Co Ltd. and Industrie 4.0 Maturity Center)

of advanced initiatives were also documented in the structural area of information systems, indicating that the right steps were being taken to drive the transformation into an intelligent, agile business. The project's goals placed particular emphasis on integrating the three sites' IT systems and fully exploiting the existing systems' potential. However, the analysis found that there was considerable room for improvement in the structural area of resources. Connecting the highly complex equipment to a management system and tracking material flows and process information in real time were found to be particularly challenging. A consolidated roadmap containing specific measures for all three sites was subsequently drawn up with what proved to be the challenging goal of standardising the measures across the three locations. Based on the requirements highlighted by the status quo analysis, a total of over seventy measures were identified in order to progressively transform Kuraray into an agile, data-driven business. The roadmap was then divided into three operational strands. These provide a conceptual framework for the measures contained in the roadmap and allow individual goals to be pursued in a structured, sequential manner. The operational strands enable a more comprehensive understanding of the processes at each site, as well as consolidated planning and management of information and material flows across the three sites and transparent asset management. The measures are prioritised on the basis of the maturity stages, taking both the time factor and strategic considerations into account. In other words, the first step is to bring together all the measures in a structural area that apply to the next maturity stage. This provides a basis for the next steps. Once this has been done, the themes that will help the company to advance in the field of Industrie 4.0 can be focused.

This process resulted in the selection of an initial batch of projects that were implemented as pilot digitalisation projects once their financial viability had been assessed. In one of the projects, an Industrial Internet of Things (IIoT) platform was chosen with the assistance of the Industrie 4.0 Maturity Center. The platform acts as a data hub, providing the central element of the IT architecture for data storage and delivery. It also provides a prioritised application system that can display targeted, real-time data. Critically, the platform is used across all three sites.

According to Christoph Lang, who is responsible for digitalisation of production at Kuraray, "the Industrie 4.0 Maturity Center and the structured, systematic approach of the Maturity Index have helped us to analyse complex processes in a structured manner, allowing us to launch and implement a number of initial projects. One project where we received further support from the Industrie 4.0 Maturity Center concerned the selection of an IIoT platform in order to optimise information and material flows across our sites."

3.5 Increasing productivity in a chocolate factory

The final case study, from 2019, describes the use of the Industrie 4.0 Maturity Index in a German chocolate factory. Individual targets were derived from the specific areas where potential was identified, providing the basis for a targeted development path. Increasing efficiency and output is a particular priority in the food industry, where there is often significant potential to make processes leaner and reduce the associated costs both in production and in indirect activities.

The status quo assessment takes about a week and is carried out using a web-based questionnaire designed to identify the current stage in the Industrie 4.0 Maturity Index. This can be adapted to a company's specific requirements by concentrating on the relevant core processes. In this particular case, the assessment focused on production planning, production, logistics, maintenance and quality assurance. Site visits and interviews with the responsible managers allowed the necessary information to be collected and documented on the spot. The individual maturity

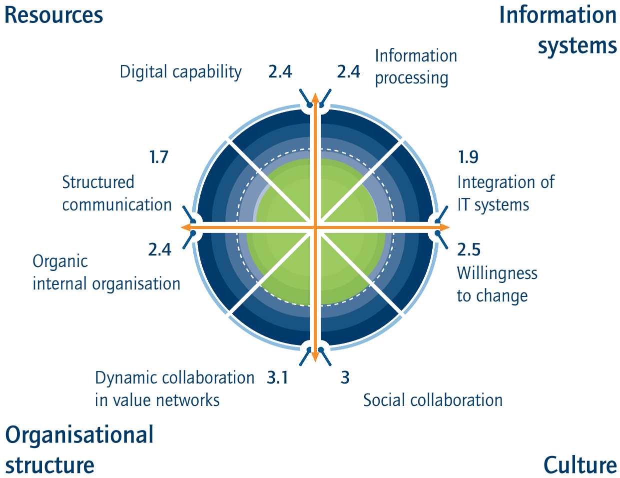


Figure 17: Aggregated results of the status quo analysis at a chocolate factory (source: Industrie 4.0 Maturity Center)

index scores are gradually built up based on a detailed assessment of specific capabilities in the individual processes. These can then be aggregated as required in order to analyse the results.

The average maturity stage score for the whole chocolate factory was 2.4. The connectivity stage has largely been achieved and this is being built on to enable a growing degree of information visibility. However, the results were far from uniform, with the individual maturity stage scores spanning a wide spectrum that ranged from 1.7 to 3.1 for the individual principles of the four structural areas of resources, information systems, organisational structure and culture (see Figure 17). Meanwhile, the scores for individual processes ranged from 1.0 to 3.7. This wide spread reveals significant variation in the progress achieved by the factory with regard to different capabilities.

A breakdown of the results indicates that the factory is already close to stage 3 in the areas of culture and organisational structure. Cross-functional collaboration is promoted and widely practised. Moreover, employees are relatively open to change and there is structured employee involvement in the company's change and improvement processes. Most of the key digital capabilities are also well developed. The machines are equipped with the technology needed to collect and process data and the interfaces to exchange it, and the factory's staff have received the corresponding training.

The main shortcoming is a disrupted information flow. Inadequate integration of the existing information systems (Enterprise Resource Planning, Manufacturing Execution System, Laboratory Information and Management System, etc.) results in media disruption that hampers the sharing and visibility of information. Consequently, communication is partly unstructured at both the employee and machine levels. General examples include widespread bilateral communication, partly paper-based documentation, manual data analysis and inconsistent use of certain systems (e.g. for production planning). One specific area with significant room for improvement is the reduction of minor machine stoppages in production. When added together, these account for a significant percentage of all downtime and thus have a considerable impact on productivity. Despite this, they are not recorded and documented in a structured manner, making it impossible to analyse them in detail and take the appropriate preventive measures.

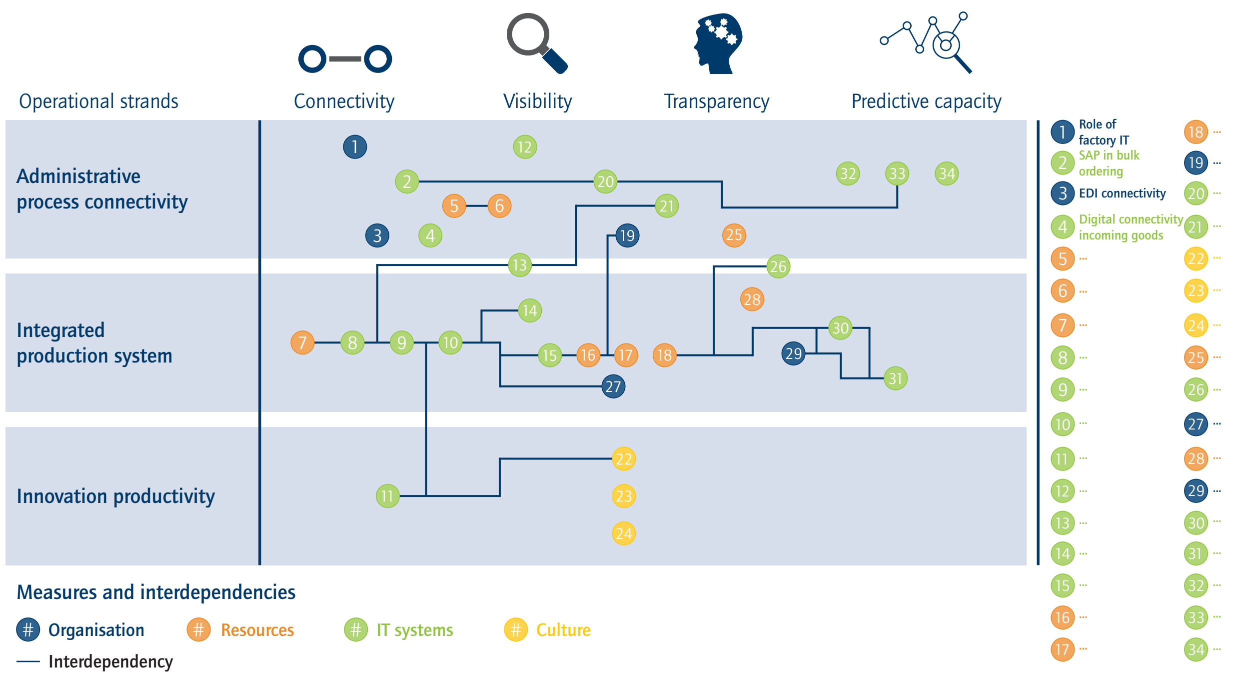


Figure 18: Digital transformation roadmap for a chocolate factory (source: Industrie 4.0 Maturity Center)

The detailed analysis of the status quo helped to identify measures to address these issues, which were then brought together in a global digital transformation roadmap. The development of the measures and their consolidation into a roadmap also takes around one week in total. In this particular case, it was decided that, in keeping with the corporate objectives, the aim should be to achieve consistent transparency (maturity stage 4) throughout the factory over the next few years. The roadmap focuses on the necessary measures to achieve this. The first step involves attaining the same level of connectivity (maturity stage 2) throughout the factory by addressing the areas that are currently lagging behind. Once the deadline for resolving these issues has passed, another status quo analysis will be carried out in order to determine what the next raft of measures should focus on. This iterative approach ensures that the measures focus on the most urgent issues that are currently causing a bottleneck and allows agile adjustments to be made to the transformation process.

The roadmap sets out the sequence of the measures and how they relate to each other. As illustrated in Figure 18, they are ordered in a partially sequential manner, with varying degrees of interdependency. As well as assigning measures to particular maturity stages, operational strands can be used to bring together the measures for particular strategic goals so that they form part of a consistent strategy. In addition to its coordinating and integrating function, the roadmap's central role is to support the internal promotion of the transformation process. In this context, it is also important to integrate current projects, since this can add extra value to existing budgets and advances by increasing employee acceptance.

The chocolate factory's digitalisation path was based on three operational strands. The first strand aims to improve the connectivity of the factory's administrative processes. It involves a range of measures geared towards improving the exchange of information throughout the production environment. Examples include end-to-end internal production planning and full supplier EDI connectivity. The second operational strand focuses on production system integration. This encompasses both production equipment connectivity and the concurrent adjustment of production processes to take advantage of the increased availability of information. Examples in this strand include automatic maintenance alert generation. The third operational strand supports the other two by aiming to strengthen innovation productivity. This strand focuses mainly on enablers such as knowledge building and management.

The roadmap contains a total of 34 measures aimed at delivering the factory's goal of achieving a digital transformation. Measures must be prioritised on the basis of their contribution to the transformation process, but it can be particularly challenging to quantify their benefits, since it is necessary to consider the indirect benefits that a measure has by enabling subsequent measures. In general, measures should be designed as specific, small-scale, short-term projects in order to facilitate greater agility. However, larger, longer-term projects are still sometimes indispensable, for instance when implementing a Manufacturing Execution System throughout the factory. In these cases, an iterative strategy should be adopted, in which the project is broken down into successive stages with their own goals and benefits. A hybrid approach in which agile projects are carried out in parallel can also help to accelerate progress. These agile projects can speed up the overall transformation process by quickly creating specific conditions that are required for subsequent measures. For example, a separate temporary system that uses simple, retrofitted sensors to analyse rejects can be employed until such a time as the necessary information is available via a fully integrated platform.

The roadmap is accompanied by detailed descriptions of all the measures in Figure 18. The descriptions include a summary of the problem and how the measure will be implemented, plus an assessment of its difficulty and scope. The benefits that can be achieved and the necessary conditions are also defined. Since many similar challenges are experienced throughout the industry and to some extent also in other industries, best practices and use cases from other companies can help with the planning and implementation of the measures. This case study demonstrates how, in a process lasting just two to three weeks, the acatech Industrie 4.0 Maturity Index can help to carry out a detailed status quo analysis and draw up a comprehensive roadmap containing specific measures in order to guide a business's digital transformation.

4 Outlook: the next steps in the digital transformation

The acatech Industrie 4.0 Maturity Index has proven its value in industry. Over the past three years, a number of manufacturing companies have assessed their Industrie 4.0 maturity stage and drawn up roadmaps for their digital transformation. Their experience shows that, at present, the most urgent need for action is in maturity stages 2 (connectivity) to 4 (transparency).

Nevertheless, over the next five years manufacturing industry will increasingly be turning its attention to the "predictive capacity" and "adaptability" maturity stages. The benefits are clear – companies that attain these maturity stages have the ability to adapt rapidly to changing circumstances.

Against this backdrop, this section examines some of the issues that companies will need to address in the medium term in the four structural areas of resources, information systems, organisational structure and culture.

4.1 Self-organising resources, agile infrastructures

In socio-technical systems, man and machine interact with each other as self-organising resources in everything from the production and assembly islands to the realisation of in-house transport processes. In Industrie 4.0 factories, this will transform rigid production and transport systems into highly agile, modular systems whose resources autonomously negotiate and carry out particular jobs. Human resources continue to play the central role in this Social Networked Industry environment – the cyber-physical systems (CPS) that cooperate with human employees adapt to them and to their specific skills and needs, especially in terms of communication and interaction.[8]

SMART FACE: an example of self-organisation in production planning and control

Self-organisation calls for a paradigm shift. Instead of production planning and control being carried out hierarchically via a central IT system, it is carried out by decentralised cyber-physical systems within the production system.[9] Funded by the Federal Ministry for Economic Affairs and Energy, the SMART FACE R&D project (Smart Micro Factory for Electric Vehicles with Lean Production Planning) used assembly stations in a model Industrie 4.0 factory to illustrate how this self-organisation could be realised:

The assembly stations comprise industrial robots, storage areas and various automated guided vehicles. Cyber-physical systems equipped with actuators, sensors and embedded software create a network in which man and machine negotiate jobs among themselves and cooperate in their execution. Decisions are based on individual rule sets that define dependencies and targets. If no dependencies are defined, the stations and the parts being processed have equal weight and are given precedence based on the relevant target (shortest route, fastest processing time, etc.).[10]

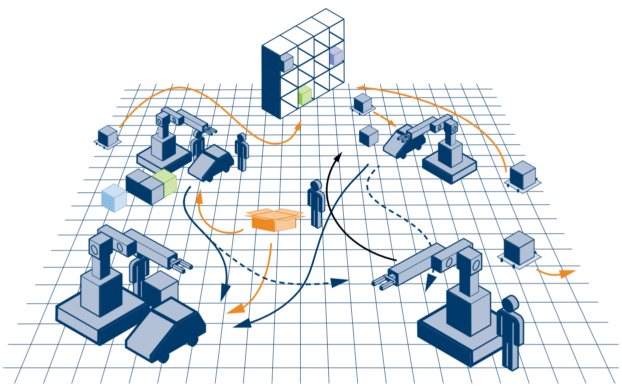


Figure 19: Self-organising resources in an Industrie 4.0 model factory (source: SMART FACE/Logata Digital Solutions GmbH)

This decentralised production control system is designed to enable extremely small batch production of electric vehicles, in response to growing customer demand for customisable products. Highly efficient but inflexible conventional assembly lines are unable to respond rapidly to changes in demand, while "craft" production systems are too slow and costly. SMART FACE enables a more flexible assembly process by using island-type workstations instead of the pearl chain model traditionally employed

8 | See ten Hompel et al. 2016, p. 3.
9 | See Müller 2016, p. 18.
10 | See Müller 2016, p. 18.

in the automotive industry. This makes it possible to implement rapid changes in the assembly sequence. The material flow is self-organising and components are supplied on demand. Moreover, if an individual station fails it does not bring the entire assembly line to a standstill.[11]

Agile infrastructures in an intelligent high-speed swarm

Conventional infralogistics infrastructures are often slow and neither modular nor scalable. But thanks to the development of a new class of automated guided vehicles, many logistics processes can now be executed extremely quickly and flexibly. The Loadrunner® is a highly efficient, modular transport robot that operates in a smart swarm. This application concept offers both high manoeuvrability and maximum autonomy. Featuring a unique load pick-up and drop-off system and operating at speeds of up to ten metres a second, Loadrunners® self-organise into swarms. They are also suitable for modular deployment thanks to their ability to couple to trailers and to other Loadrunners®.[12] The high speeds at which these vehicles operate place particular demands on their sensors, as well as requiring extremely precise positioning technology and a high degree of manoeuvrability. In addition to their use as an alternative to baggage handling systems in airports, other intralogistics applications include highly dynamic package sorting and the execution of production logistics processes. As well as simply performing physical processes, the Loadrunner's® ability to negotiate and carry out jobs and the highly intelligent way in which it connects not just with other members of its swarm but also with people and platforms means that it has the potential to play an important role in the Silicon Economy.[13]

4.2 Artificial intelligence for industrial applications

The operational deployment of cloud and edge technologies in order to achieve horizontal and vertical integration of a company's IT architecture is a complex infrastructure measure that makes it possible to attain the higher Industrie 4.0 maturity stages in the digital transformation. Integrated analysis and implementation that takes account of commercial factors, the expandability of the technology and autonomous sovereignty is key when selecting the right platform provider to partner with.

Regardless of the underlying data infrastructure or service platform, the concept of administration shells[14] provides a framework for managing distributed, heterogeneous production asset data (see Figure 21). The administration shell allows legacy system asset data – i.e. data from different sources and in different formats – to be brought together logically in a single location, ultimately creating a digital twin of the asset. An administration shell clearly identifies its asset and describes it over the entire course of its life cycle. To do this, it references component models distributed across the network, that are connected "downwards"

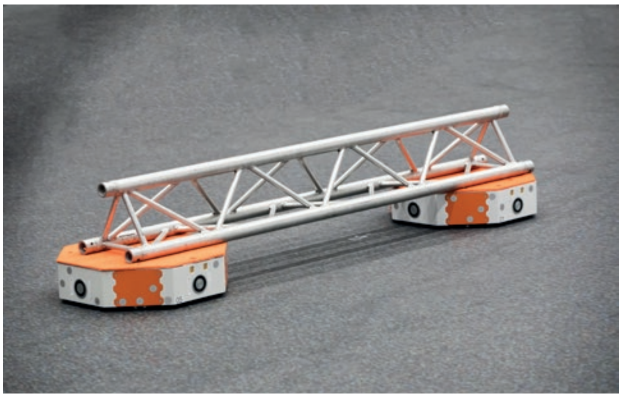


Figure 20: Collaborative transportation of a crossbeam (source: Michael Neuhaus/Fraunhofer IML)

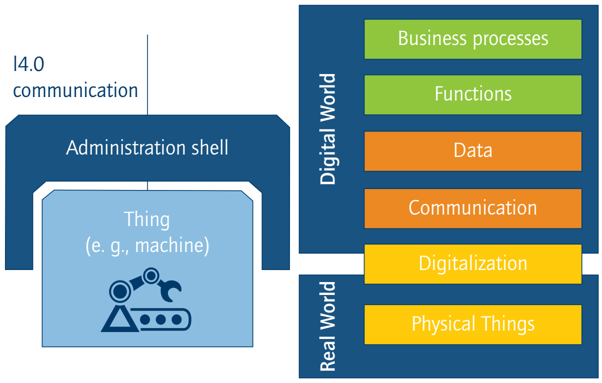


Figure 21: Schematic diagram of an administration shell (source: Contreras et al. 2017)

11 | See BMWi 2016, p. 40 f.
12 | See Fraunhofer IML 2020, p. 12.
13 | See Fraunhofer IML 2020, p. 12.
14 | See BMWi 2019b.

to a legacy system while also being able to communicate asset data and functions "upwards" in the language of the administration shell. The elements of a component model – i.e. defined properties, operations and events – can be annotated with semantic concepts governed by global standards such as the Common Data Dictionary,[15] the eCl@ss dictionary[16] and other sectoral ontologies.

In the future, this approach will result in semantic interoperability which, in contrast to today's isolated solutions, will enable industrial AI applications that can be used across entire departments, divisions or even companies for purposes such as optimising productivity. By their very nature, these AI applications are also portable, since administration shells are technology-neutral and not tied to a particular platform provider. In the context of edge technology, the term "Edge AI" has already been coined to describe the use of AI solutions on the edge. There are a number of additional challenges that need to be addressed in this area. The first question is how efficient modelling – e.g. for machine learning on the edge – would work if the necessary data are not available in the (on-premises) cloud, which is after all far more powerful than the edge node. Continuous updating is another aspect that is currently being investigated, together with the associated strategies for efficient, secure and automated deployment of AI models on the edge.

While the main focus of existing platforms is to add value during the production phase, an end-to-end approach to the entire product life cycle has the potential to deliver further optimisations. The challenge is to guarantee trackability throughout the product life cycle and traceability in order to optimise value creation. In this context, the use of administration shells at the data and model level creates interoperability between production and upstream engineering, accelerating innovation cycles to the point where continuous engineering is achieved. Model-based systems engineering (MBSE) uses models to support specifications, design, analysis, verification and validation throughout every stage of the product life cycle. It replaces document-based systems engineering methods with an approach based on data-driven system models, making it possible to add value by highlighting previously unidentified optimisation potential (see Figure 22).

4.3 Changes in the interactions between humans, organisations and technology

Despite the fact that new technologies offer significant opportunities, small and medium-sized enterprises (SMEs) in particular can be reluctant to deploy them. This is not so much due to the technical challenges as to the rather indeterminate risks to their organisation and employees. Even if new technologies such as assembly assistance systems are successfully installed, their value-added operation is heavily dependent on compatible processes, appropriate skills and employee acceptance. This means that rather than being a purely technical matter, Industrie 4.0 affects humans, technology and organisations in equal measure. The term "socio-technical system" describes the interactions between these three dimensions. When introducing Industrie 4.0 solutions,

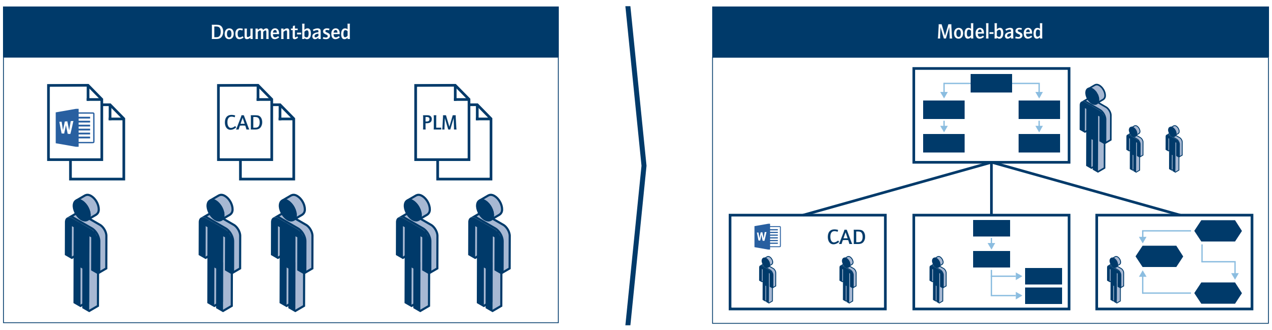


Figure 22: The switch from document-based to model-based product engineering (source: Department of Computer Integrated Design (DiK), Technical University of Darmstadt)

15 | Further information available at https://cdd.iec.ch/.
16 | Further information available at https://www.eclass.eu/index.html.

it is important to consider these interactions between humans, technology and organisations.[17]

Companies considering implementing an Industrie 4.0 solution in their business will need to identify its potential impacts and in particular the associated risks. These companies must acquire the ability to identify socio-technical risks at an early stage and develop strategies and measures that minimise the risks of introducing Industrie 4.0 solutions. To do so, they can employ classical risk management techniques[18] for identifying, analysing, evaluating, managing and monitoring the risks in question.[19] However, in each of these steps it is important to address the interactions that constitute the socio-technical dimension.

A variety of different risks are associated with the introduction of Industrie 4.0 solutions. Examples include employee surveillance issues connected to the collection of personal data, difficulty managing the deluge of information generated by assistance systems, overcomplicated operation of assistance systems, inadequate digital system data maintenance and a reluctance to change within the company.[20] These examples illustrate the diverse nature of the risks involved in introducing Industrie 4.0 solutions – but these risks are not always immediately obvious to companies. This problem can be countered through the systematic compilation of risk categories.[21] Each risk category has a set of indicators that allow the scale of a risk's potential impact to be assessed so that all the relevant risks can be prioritised.[22]

The results of the risk identification and assessment process provide the basis for risk management, i.e. the development of an appropriate risk strategy for the company. The risk strategy sets out guidelines for the implementation of risk management programmes. The packages of measures that make up these programmes must be carefully coordinated, since each individual measure can trigger further socio-technical interactions. For instance, a lack of employee acceptance can be countered by appointing technology promoters[23] responsible for communicating information about new technologies in the company. Technology promoters can help to reduce employees' prejudices about a new technology by explaining how it will bring significant benefits. The appointment of a technology champion means that the measure will also have an impact on the organisational dimension, since the function of the employee in question will need to be redefined and their responsibilities determined. Well-coordinated packages of measures take all of these interactions into account, ensuring that the measures taken to manage existing risks do not themselves give rise to new risks.[24]

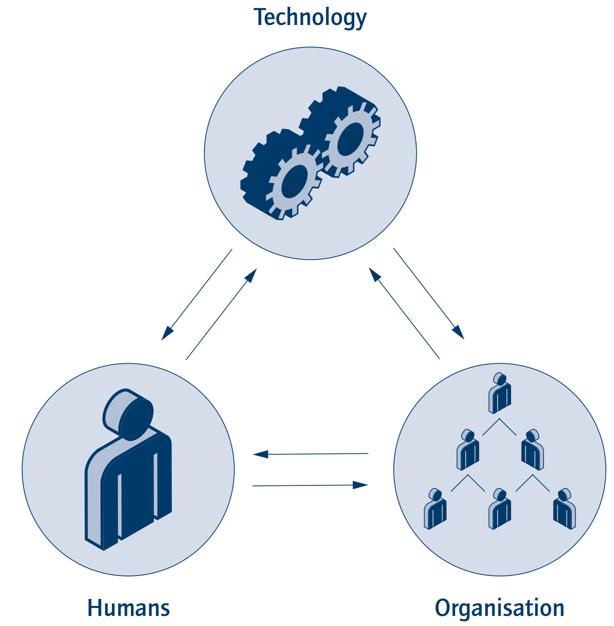


Figure 23: Humans, technology and organisation (source: Heinz Nixdorf Institute, Paderborn University)

During the introduction of Industrie 4.0 solutions, the risks should be continuously monitored and reviewed. Premise control and goal monitoring techniques can be employed to support risk management by identifying discrepancies at an early stage and adapting the risk management measures accordingly.[25]

By taking socio-technical interactions into account, integrated risk management minimises the risks of introducing Industrie 4.0

17 | See Hirsch-Kreinsen et al. 2016, p. 10 f.
18 | See Brühwiler 2008, pp. 26–27.
19 | See Oehmen 2019, p. 10.
20 | See Dumitrescu et al. 2017, p. 7 f.
21 | See Wolke 2008, p. 201 ff.
22 | See Wolke 2008, p. 11 ff.
23 | See Walter 1998, pp. 103–106.
24 | See Schwarz 2016.
25 | See Sorger 2008, p. 135 f.

solutions.[26] Moreover, by ensuring coordination of the risk strategy and the company's corporate strategy, risk management can help to adapt the corporate strategy to digitalisation.

4.4 Management and Leadership "4.0" in the digitalised workplace

The increasing digitalisation of the workplace is resulting in the transformation and realignment of companies' internal processes. Executives play a key role in shaping digitalisation within companies, since ultimately they are responsible for its successful rollout. As with other change processes, executives must successfully overcome a variety of contradictions and conflicts of interests.[27] However, digitalisation adds an extra dimension to the mix, since all of a sudden executives have to look at their own role and try to determine what shape, if any, management and leadership should take in a digitalised company, bearing in mind the need to maximise effectiveness and efficiency. Indeed, it is frequently suggested that digitalisation could lead to companies dispensing with management and leadership altogether.[28] To respond competently to these challenges, executives must possess a sophisticated understanding of the nature of management and leadership.

In essence, leadership is a means of influencing people's behaviour. Typically, this involves an interaction between people – it is an activity that takes place between human beings. Its goal is to bring about a conscious change in behaviour in areas such as "capabilities" (training and learning), "willingness" (motivation), and "socially acceptable or expected behaviour" (values and norms) (see Figure 25).[29]

While digitalisation makes communication simpler and faster, the new forms of communication also require structural and cultural changes. In the future, hierarchies will become less important and the balance of power will shift. The nature of knowledge is also changing fast as it becomes more and more specialised and compartmentalised. This can lead to employees becoming experts in possession of exclusive knowledge that is hard to control.[30] As a result, executives may no longer have as strong a monopoly of power within their company as they did before digitalisation. Moreover, digital systems such as planning tools make it easier

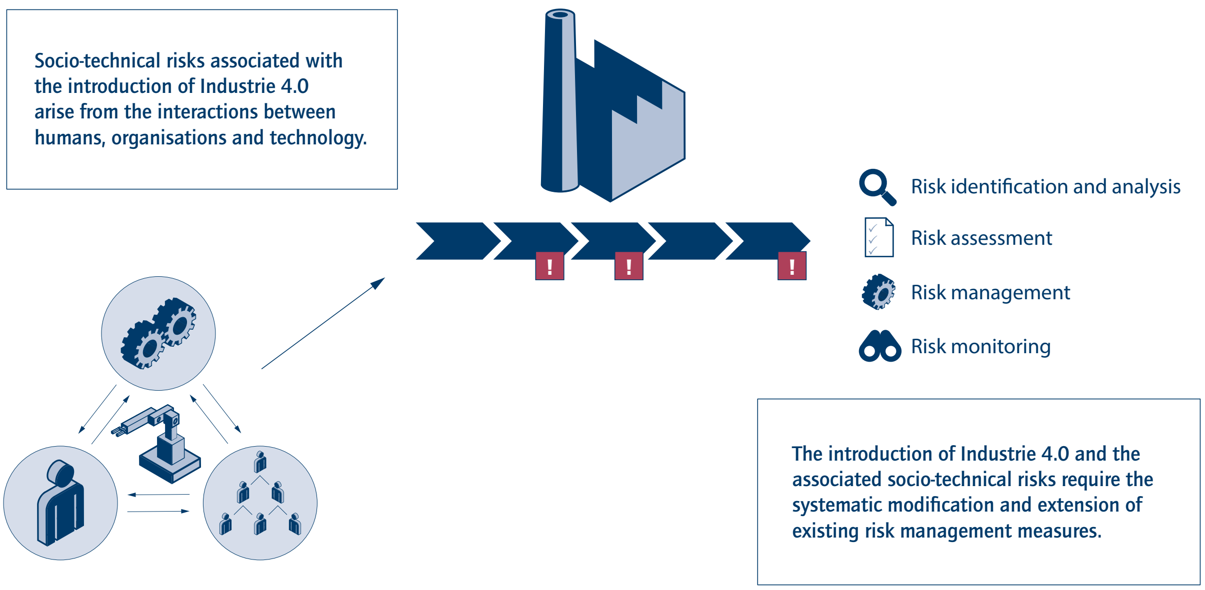


Figure 24: Socio-technical risks throughout the entire value chain (source: Heinz Nixdorf Institute, Paderborn University)

26 | The joint project "Sociotechnical Risk Management During the Introduction of Industrie 4.0 (SORISMA)" addresses integrated risk management when implementing Industrie 4.0 solutions. The project has received funding of approximately €2.7 million from the European Regional Development Fund (ERDF).
27 | See Claßen 2019.
28 | See Weber et al. 2018.
29 | See Weibler 2016.
30 | See Volkmann 2019.

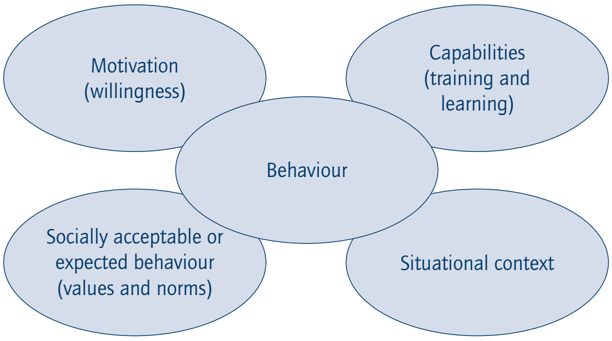


Figure 25: Influences on people's behaviour (source: Industrie 4.0 Maturity Center, FIR e. V. at RWTH Aachen University)

for employees to perform their duties, helping them to manage themselves and thereby reducing the workload for executives.

These changes will require executives to take on different roles and functions within the companies. It is not yet clear which responsibilities and duties will no longer be performed by executives and whether they will be primarily strategic, tactical or operational in nature. There has been very little research into this question, and the diverse nature of roles in different departments (e.g. shop floor), companies and sectors (e.g. crafts and industry) means that there are no one-size-fits-all answers. What we do know is that the nature of management and leadership will change – some functions will disappear and new functions will replace them. Executives will increasingly take on the role of coaches or mentors. In other words, they will perform more of a support function, focusing on team spirit, mood, common values and guiding the development of self-managing teams.

We are now witnessing the introduction of new organisational concepts, particularly by young companies in digitally savvy industries. One example is the holacracy[31], which is based on roles and responsibilities rather than traditional hierarchies (see Figure 26). A central rule set that can be continuously developed helps to steer the company. Holacracies prefer to avoid major changes of direction, favouring rapid minor course corrections instead. They seek to build a consensus rather than taking decisions by majority vote. In this type of setting, it is probably no longer meaningful to talk of "management" or "executives". This approach is illustrated by Markus Stelzmann of Vienna-based manufacturing company Tele Haase, who has abolished traditional executives and likens his role to that of a film director: "I am a lobbyist for themes, fairytale teller, kindergarten teacher and suggestion box, and maybe also a kind of mentor". It so happens that in my role as the "movie director" in the support process I am also allowed to do things like sign off balance sheets and speak to banks. I suppose I act as the counterpart for all those 'external' entities that still need to deal with someone in a 'managing director' role."[32]

Does this really mean that there will no longer be a need for management or leadership? If, at its core, leadership is understood as a means of influencing people's behaviour, then it will not disappear as a result of digitalisation – it remains a key function, even in

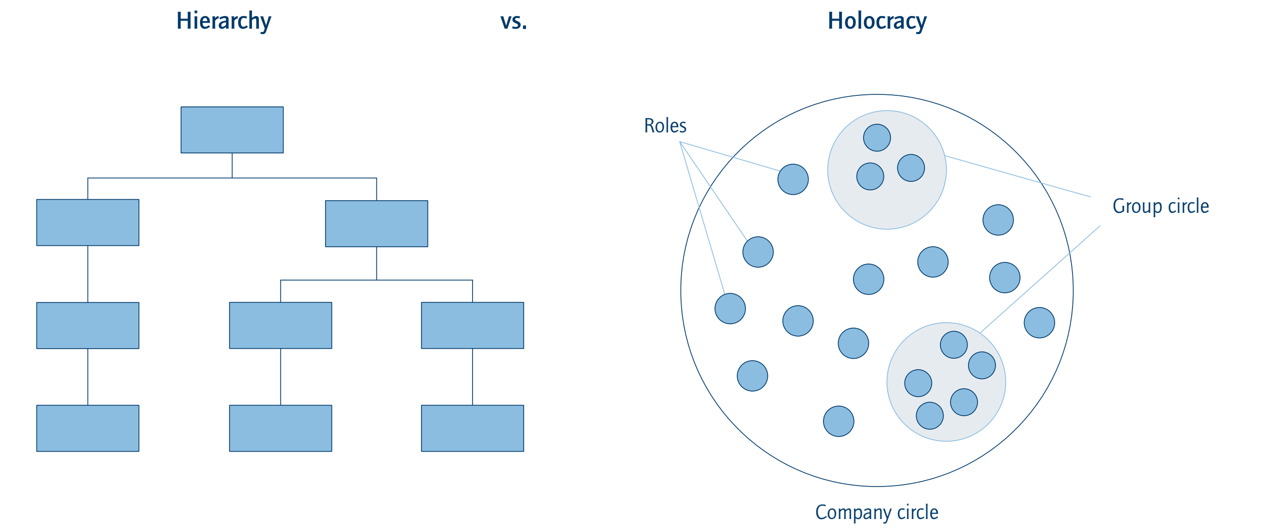


Figure 26: Traditional hierarchy versus holacracy (source: Industrie 4.0 Maturity Center, FIR e. V. at RWTH Aachen University)

31 | Further information is available at https://www.holacracy.org/.
32 | See https://www.tele-online.com/team/stelzmann-markus/.

self-managing teams. Nevertheless, the executive profession could undergo fundamental changes or even come under threat in its entirety. In models such as the holacracy, management or leadership is no longer tied to individuals but is seen instead as a function that a company can call up as and when necessary. In these models, management or leadership is implemented as a distributed, pluralistic process. Companies must be able to recognise when the management and leadership function is required and who should perform it in any given situation. In these settings, all employees must in principle be capable of performing management and leadership duties, but no-one is permanently designated as a manager or leader. Management and leadership must become a general skill and the company must create a culture of learning to ensure that all its employees develop the corresponding competencies. Rather than simply importing isolated, individual new work practices, it is important to find the right configuration for each company. All the elements must interact effectively with each other and be tailored to the company's employees, their skills and the industry in question. It is also important for executives to perceive digitalisation as an opportunity.

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Manufacturing industry in Germany has realised that the fourth industrial revolution cannot be accomplished simply through the implementation of individual, isolated prototypes – a systematic transformation programme is required, focusing on clear financial value added. Since the publication of the acatech STUDY in 2017, the acatech Industrie 4.0 Maturity Index has proven its worth as a tool offering practical guidance on how to achieve a structured, integrated digital transformation in companies.

The practical examples in this companion publication show how the Industrie 4.0 Maturity Index has been used to add value in a variety of different businesses, from automotive suppliers to chemical companies. A roadmap that prioritises and structures a company's digitalisation measures can help to prevent common mistakes such as fragile information system integration or inadequate employee involvement. This approach benefits companies by enabling a systematic and cost-effective transformation into an agile, learning organisation.