A PORSCHE COMPANY

INDUSTRY 4.0 BAROMETER 2026

Software-Defined Manufacturing – The New Foundation of Industrial Competitiveness

Contents

Summary

Who should read the Industry 4.0 Barometer?

The Industry 4.0 Barometer 2026 provides a comprehensive overview of the current status of Industry 4.0 implementation in companies and is aimed at anyone who wishes to actively shape the digital transformation in manufacturing.

Company management, executives, and department heads will gain in-depth insights into the current status of Industry 4.0 implementation. They will learn where the use of technologies such as Digital Twins, autonomous systems, or Artificial Intelligence varies, and what potential for efficiency, transparency, and data-driven optimization can still be tapped. Practical interviews and success stories provide concrete best practices and demonstrate which approaches have proven successful in real-world production operations. Particularly valuable are the findings on this year's focus topic, Software-Defined Manufacturing (SDM): They provide insights into the international status quo, identify key challenges and success factors, and highlight the technological and organizational prerequisites for successful implementation. The concluding recommendations for action provide a practical roadmap for the targeted promotion of efficiency, resilience, and future-proof business models.

Internationally active companies also benefit from the benchmark comparison: They can see where the DACH region stands in global competition, what strategies are being pursued by pace-setting countries such as China and India, and which approaches are particularly effective for modernizing, transforming, and scaling production processes.

Academia, policymakers, and trade associations also gain valuable insights: The robust data on Industry 4.0 trends, obstacles, and opportunities support the development of funding initiatives, strategic frameworks, and innovation programs, and help to better understand the digital transformation of markets and companies.

In short, the Industry 4.0 Barometer 2026 provides a solid foundation for strategic decisions, practical guidance, and scientific analysis, and is aimed at anyone who wants to not only observe Industry 4.0 but also actively shape it.

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Industry 4.0 Barometer 2026
On behalf of MHP Management- und IT-Beratung:

Many thanks to all participants and experts for their assessments and opinions. This study would not have been possible without your support. Special thanks go to Ludwig Maximilian University (LMU) Munich for our successful and consistently productive collaboration.

Foreword

Dear Readers,

While markets such as China and the U.S. are already widely adopting agile, data-driven production strategies, many European companies remain trapped in rigid structures, data silos, and fragmented IT landscapes. This represents a dangerous lag behind global competitors, which, according to our Industry 4.0 Barometer data series, has been glaringly evident for several years now.

This year's Industry 4.0 Barometer, now in its eighth edition, once again clearly demonstrates that companies that do not develop the ability to plan and produce in a flexible, data-driven manner as quickly as possible are putting their competitiveness at risk – and, in some cases, the very survival of their business.

Through our global benchmark study, we can compare trends over the past few years and see that Europe is steadily losing ground: Our calculated overall barometer score, used as an indicator, is rising internationally from 48 percent (2022) to 66 percent (2026), but the DACH region is lagging significantly behind: It is stagnating at 57 percent, while, for example, China, at 72 percent (up 3 percentage points), and the U.S., at 69 percent (up 3 percentage points), are even showing growth at their already high levels.

A key aspect in this regard is the digital mapping of production and logistics processes. While 84 percent of companies in China use digital twins in logistics, this is only the case for only 42 percent of companies in the DACH region. In this context, SDM is more than a buzzword – it is a tool for survival. By decoupling production control from hardware, a central software layer is created that makes manufacturing flexibly scalable, cross-location, and ready for innovation. Artificial Intelligence, the Industrial IoT, and even the Industrial Metaverse are no longer just a distant dream – they are becoming a reality in the workplace. However, only three (!) percent of respondents in the DACH region are familiar with the concept of SDM. In China and India, that figure is 30 percent.

There is no point in denying it – it's time to stop watching and start taking action. However, the international differences also reveal where the greatest levers and opportunities lie. Technologies such as SDM, AI-powered planning, and the Industrial IoT are now mature, available, and field-proven.

First and foremost, I would like to thank our research team at MHP, who put together this report with passion and perseverance. Special thanks also go to Professor Dr. Johann Kranz from the Ludwig Maximilian University (LMU) Munich, our long-standing and loyal study partner. And a huge thank you to the more than 1,200 participants worldwide, as well as to the numerous experts who contributed their insights to this year's Industry 4.0 Barometer.

We need to regain not only our technological sovereignty but also our industrial sovereignty. I hope you find the insights in this report exciting and thought-provoking.

Yours sincerely, Markus Wambach

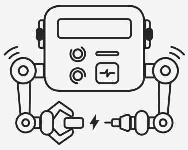
Group COO | MHP Management- und IT-Beratung GmbH

General

Key findings

China is shaping the factory of the future – Europe is struggling with the past

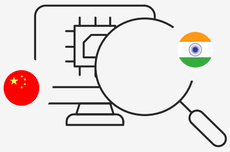
China is taking the lead in supply chain transparency, digital twins, automation, and AI, and is consistently leveraging cutting-edge technologies to boost production, efficiency, and competitiveness. In an international comparison, the DACH region and the United Kingdom are mostly lagging behind: Outdated infrastructure, network quality issues, and existing legacy systems are slowing down the implementation of new digital solutions, leaving Europe behind the global leaders.



The AI paradox: high expectations, low maturity

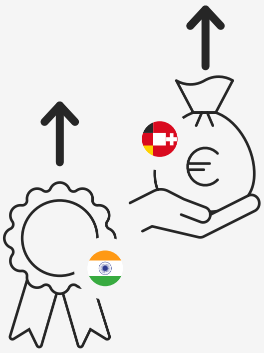
Our study shows that many companies have so far only used AI on a pilot basis, while deep integration into production processes is still in its infancy. At the same time, the future impact of AI is highly anticipated. However, in manufacturing, AI cannot be “simply activated” – first, the necessary foundations, such as data infrastructures, sensors, and digital twins, must be established before smart algorithms can have a productive impact.

The AI hype gap makes it clear: Without these foundations, AI in industrial practice often remains an ambitious promise for the future rather than an effective productivity lever.



India and China are setting the pace in data analytics capabilities – the DACH region is falling behind in a global comparison

The international results paint a clear picture: While India and China are systematically expanding their data-driven production capabilities and setting the pace for automated decision-making, the DACH region is lagging far behind. Legacy IT and OT landscapes, fragmented data structures, and high integration costs are holding back progress in this region – despite the fact that the necessary investment funds are available. Therefore, this lag is less a reflection of a lack of ambition than a consequence of technical debt, which significantly hinders the transition to scalable data analytics.

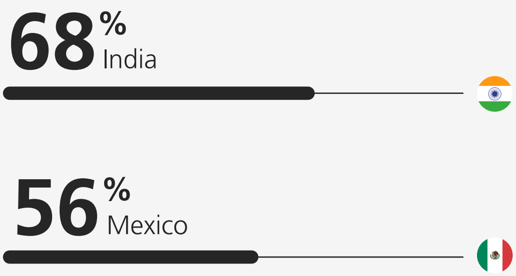


DACH optimizes costs – emerging markets focus on growth

The DACH region remains strongly focused on efficiency and cost optimization, which means that opportunities for growth, flexibility, and innovation often remain untapped.
In contrast, emerging markets such as India, China, and Mexico are pursuing more nuanced strategic objectives. For example, due to its historical competitive position and global pressure, India is deliberately focusing on improving quality in order to meet international standards and open up new markets.

Obstacles are rising – data silos are increasingly seen as a barrier

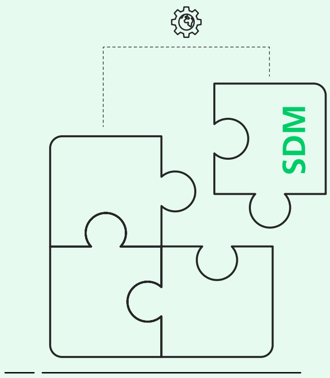
On average, obstacles are rated as most significant in India and Mexico. It is also worth noting that, compared to the previous year, existing data silos are increasingly viewed as a barrier in all regions. The figures for the newly surveyed regions are particularly high in this regard, at 68 percent in India and 56 percent in Mexico.



Obstacles are rated particularly high in the newly surveyed regions.

Software-Defined Manufacturing

Key findings



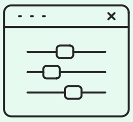
Software-Defined Manufacturing is becoming a key capability globally – the DACH region is losing ground

Internationally, Software-Defined Manufacturing is seen as a key driver for the future of manufacturing. While other regions are resolutely investing in software-based core capabilities, the DACH region is visibly losing pace. Industrial leadership is increasingly shifting toward markets with strong software capabilities – with long-term implications for competitiveness and value creation.

Production architectures are being designed in a modular, software-centric manner – the DACH region is digitalizing too late

Leading industrial regions develop modular, software-controlled production systems from the outset. In the DACH region, digitalization is often applied to existing structures only at a later stage. This approach limits scalability, speed, and the capacity for innovation – and creates a structural disadvantage compared to "digital-by-design" architectures.

FEATURED TOPIC

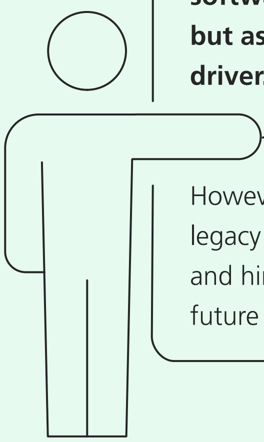


Real-time data is available – but data expertise determines the competitive edge

Today, high-quality production data is available almost everywhere. The difference lies in how it is used: While other markets are establishing AI-based, highly automated, real-time decision-making, the DACH region often gets stuck in the analysis phase. It is not data collection but data-driven management that determines productivity and competitiveness.

Organization, leadership, and investment logic are holding back transformation – the CIO is taking on a key role

Many companies already possess the technological foundations for Software-Defined Manufacturing. The biggest hurdles lie in established organizational structures, silos, and decision-making logics. At the same time, the role of the CIO is shifting: from a traditional IT operator to an architect of the industrial future.



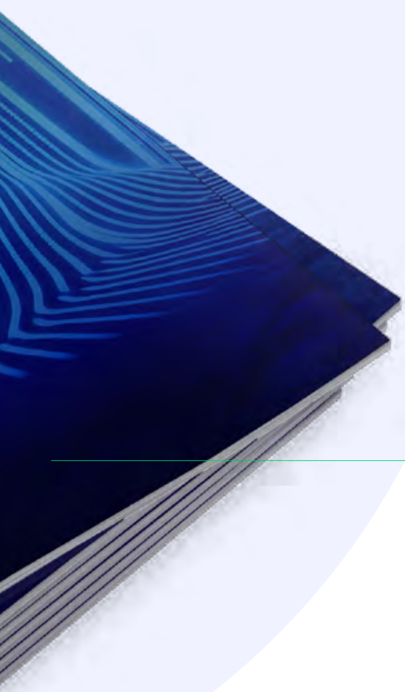
Software-Defined Manufacturing requires clear prioritization, new governance models, and an investment logic that views software not as a cost item but as a strategic value driver.

However, technical debt and legacy systems tie up budgets and hinder the necessary future investments.

IT/OT integration becomes the digital control center of the modern factory

The separation between office IT and shop floor IT is increasingly seen as outdated. Companies that consistently integrate IT and OT achieve transparency, speed, and the foundation for automation and self-optimization. As a result, IT/OT integration becomes the factory's central control entity – and a fundamental prerequisite for adaptive, software-driven production systems.

1. Introducing to the Industry 4.0 Barometer 2026



General Barometer Section

- Technology
- IT Integration
- Strategy and Goals
- Obstacles

FEATURED TOPIC Software-Defined Manufacturing

1.1. Content focus

The adoption of Industry 4.0 is steadily advancing, and at many companies, it is already an integral part of production operations. The Industry 4.0 Barometer examines, across industries and regions, how companies are putting Industry 4.0 into practice, what their understanding of the Fourth Industrial Revolution is, and how far advanced they are in implementing relevant technologies. The study provides valuable insights into both existing challenges and potential opportunities, and shows how companies can address shortcomings, seize opportunities, and enhance their competitiveness.

To provide a comprehensive overview, MHP, in collaboration with Ludwig Maximilian University (LMU) Munich, is examining the current state of Industry 4.0 implementations for the eighth time. This annual benchmark study provides up-to-date insights into the activities of companies in the so-called DACH region (Germany, Austria, Switzerland), the United Kingdom (UK), the United States, China, and, for the first time, India and Mexico.

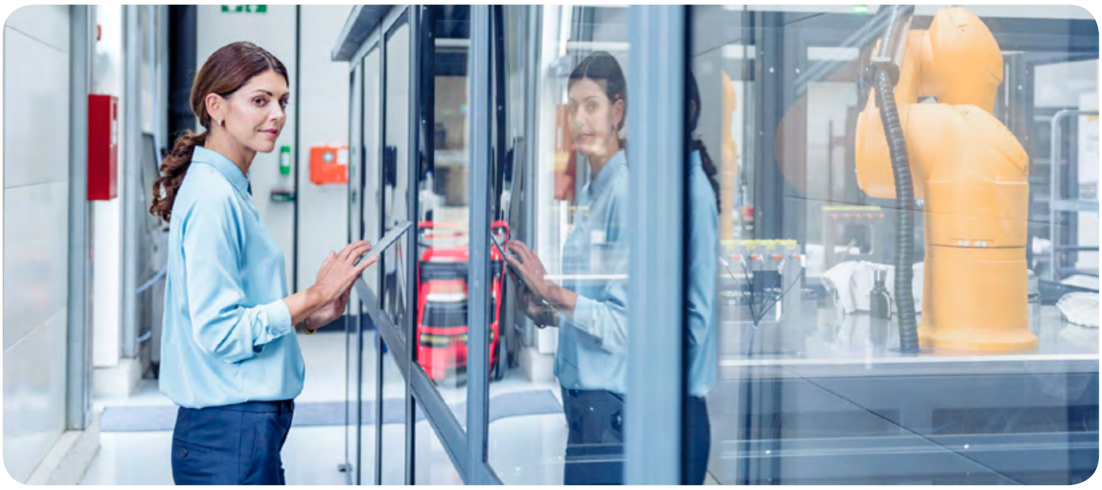
Each year, the questionnaire used covers four key topic clusters:

Technology
Efficient use of Industry 4.0 technologies (supply chain transparency, digital twin, automation and autonomous systems, artificial intelligence)

IT Integration
Enhancing the performance of the company's internal IT infrastructure (IT architecture, IT security, scaling of IT systems, and data analysis capabilities)

Strategy and Goals
Strategic focus of Industry 4.0 activities

Obstacles
Negative factors for the implementation of Industry 4.0 technologies



Current digitalization trends are incorporated into the study each year, ensuring that the Barometer always reflects the latest developments. The Industry 4.0 Barometer 2026 focuses on Software-Defined Manufacturing (SDM). This focus topic centers on the flexibility, modularity and software-based control of production systems. At its core, the aim is to define production processes in a more software-based manner, to connect them, and to adapt them dynamically to changing requirements. SDM enables the seamless integration of data, machines, and control systems, allowing production processes to be made smarter, more efficient, and more scalable. By linking the physical and digital realms, decisions can be made in real time, resources can be used optimally, and processes can be continuously optimized. SDM not only supports operational efficiency but also lays the foundation for strategic innovation, enhanced resilience, and sustainable competitiveness.

1.2. Evaluation methodology

The Industry 4.0 Barometer 2026 provides a detailed overview of the state of development of companies from various sectors in the area of Industry 4.0 in the survey year 2025. The study is based on a detailed questionnaire that includes various five- and seven-point Likert scales to capture respondents' answers in a nuanced manner. The results are grouped into topic clusters and converted into percentage values – known as barometer values – which are calculated as the weighted arithmetic mean of the responses.

In addition, for response options that involve prioritization, respondents can distribute 100 points among various options. In this process, the original Likert scale values are transformed into metric scales (0–5 or 0–7, respectively) and combined with the relative frequencies of the responses to calculate barometer values ranging from 0 to 100 percent. These barometer values serve as benchmarks and allow the results to be compared based on various characteristics of the participants and their companies. The survey was conducted anonymously to ensure valid and representative insights.

1.3. Participants

The results of the Industry 4.0 Barometer 2026 are based on responses from a total of 1,206 participants from various regions. This includes 200 respondents from the DACH region, 202 from the United Kingdom (UK), 200 from the United States (U.S.), 200 from China, 200 from India, and 204 from Mexico (Figure 1).

Distribution of respondents by region

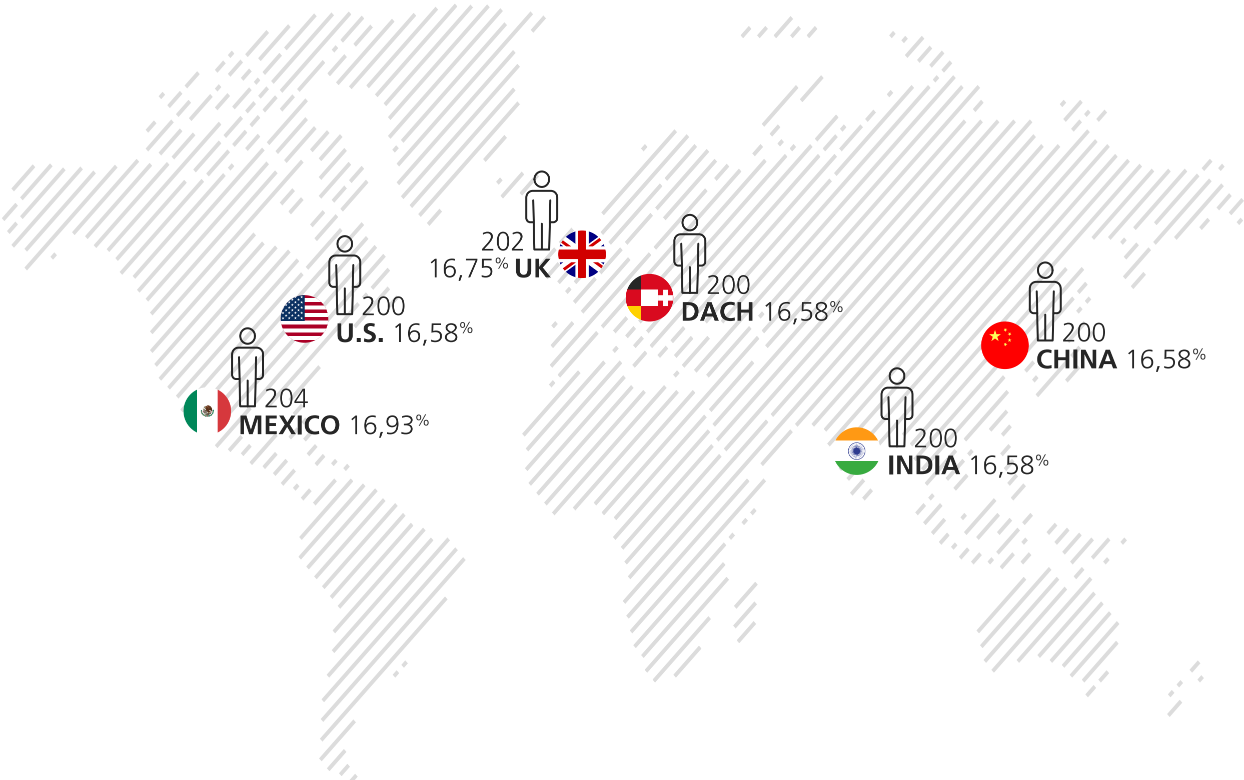


Fig. 1: Distribution of respondents by region / n – 1,206

An analysis of the company sizes of the survey participants reveals a diverse picture:
61 percent of the respondents come from small and medium-sized enterprises (SMEs) with fewer than 1,000 employees, 27 percent work in companies with 1,000 to 10,000 employees, and 12 percent are employed in companies with more than 10,000 employees (Figure 2).

Distribution of respondents by company size

Fig. 2: Distribution of respondents by company size / n – 1,206

The survey includes individuals from all hierarchical levels, from operational staff to top management. The majority of respondents (81 percent) can be classified hierarchically as belonging to the third level or lower below senior management. Information and communication technology and mechanical and plant engineering are the most strongly represented industries, each accounting for 13 percent of respondents, followed by the automotive industry (OEMs and suppliers combined), which accounts for 10 percent of respondents (Figure 3).

Distribution of respondents **by industry**

13% Information & Communication Technology

13% Mechanical & Plant Engineering

10% Automotive (OEMs & suppliers)

- 7% Construction
- 7% Electrical & Electronics
- 7% Consumer goods
- 6% Furniture industry
- 6% Other
- 5% Medicine/Healthcare
- 5% Metal production & processing
- 4% Retail & Wholesale
- 3% Chemicals
- 3% Textiles & Apparel
- 3% Energy & Water management
- 3% Transportation & Logistics
- 2% Plastics industry
- 1% Agriculture & Forestry
- 1% Communications/PR/Advertising
- 1% Paper & Printing

Fig. 3: Distribution of respondents by industry / n – 1,206

The most frequently represented specialist departments are Production (24 percent) and IT (23 percent). This is consistent with the key findings of the Industry 4.0 Barometer (Figure 4).

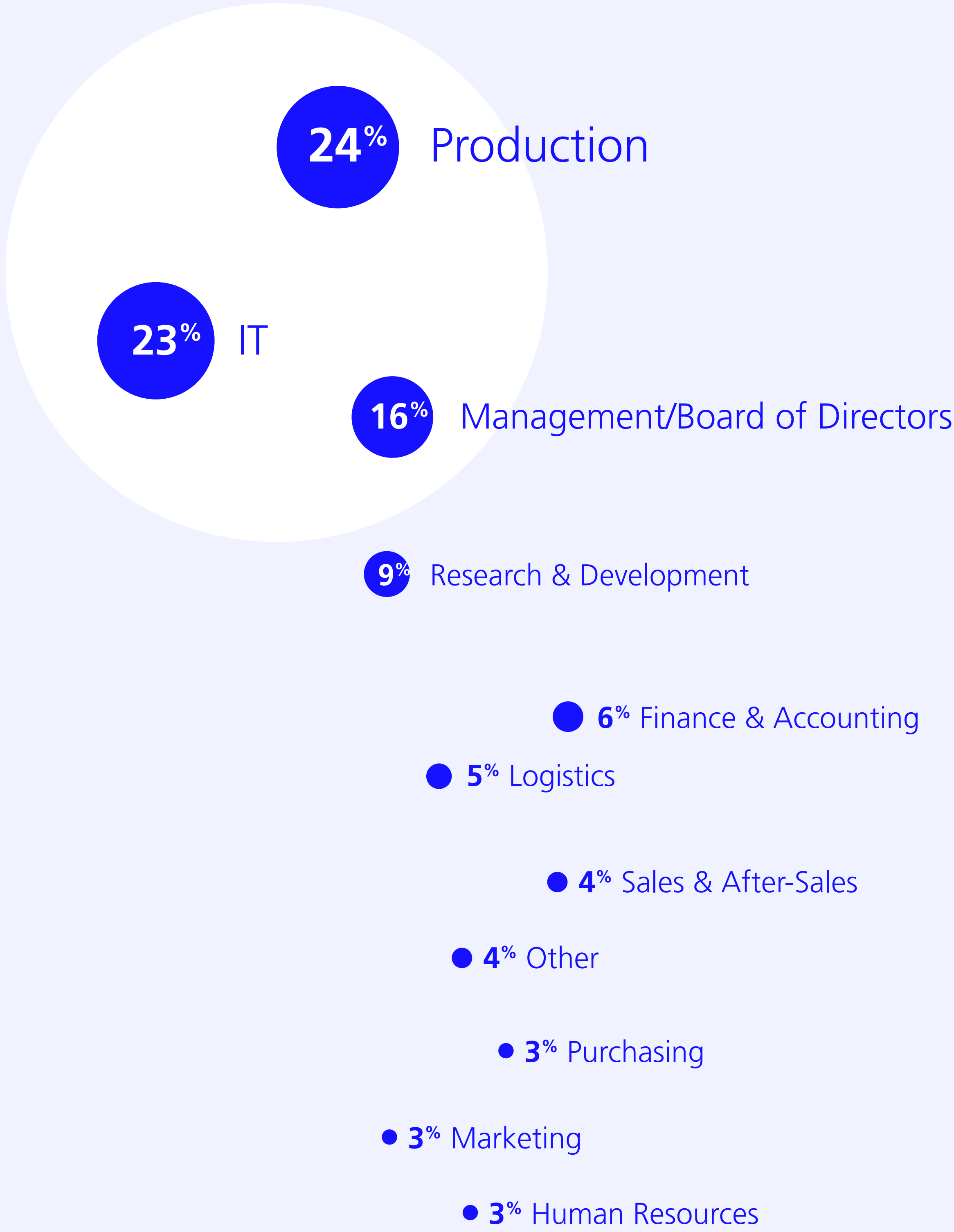


Fig. 4: Distribution of respondents by department / n – 1,206

1.4. Interviews and Success Stories

In addition to analyzing the survey results, the Industry 4.0 Barometer also features interviews with leading industry experts and MHP success stories that illustrate the practical application of Industry 4.0 technologies. In these interviews, the experts interviewed not only provide insights into the focus topic of Software-Defined Manufacturing, but also share their personal assessments of the state of digital transformation in industry. They were also asked about specific use cases and digitalization projects within their own organizations.

Interviews were conducted with the following experts:

Interview on page 22

Bernd Reitmeier

CEO
(Startup Factory China)

An interview with Bernd Reitmeier, CEO of Startup Factory China, who has witnessed China's transformation over the past 27 years, from a low-wage country to high-quality production and rapid innovation cycles.

Interview on page 86

Chris-Markus Kratz

Global Director Automotive & Manufacturing
(Amazon Web Services)

An interview with Chris-Markus Kratz, Global Director Automotive & Manufacturing, at Amazon Web Services, entitled "Courage pays off: From the cloud to the dynamic shop floor with Software-Defined Manufacturing"

Interview on page 78

Lutz Kramer

CEO
(V4Smart)

An interview with Lutz Kramer, CEO of V4Smart, on the topic of "Software-Defined Manufacturing and real-world power: Insights into new battery production at V4Smart"

The MHP Success Stories present real-world use cases of data-driven production, with a particular focus on the implementation of advanced, software-based production and logistics solutions. In addition to the initial challenges faced by the companies, the focus is primarily on the specific implementation process and the improvements achieved. Our latest example of this is the digital transformation of manufacturing and intralogistics at ElringKlinger, where paper-based production has been replaced by an integrated and scalable system landscape. By adopting SAP Digital Manufacturing (SAP DM) and SAP Extended Warehouse Management (SAP EWM) and implementing key building blocks of Software-Defined Manufacturing (SDM), ElringKlinger created an end-to-end, data-driven process control system.

Through standardized interfaces such as OPC UA, uniform data models, and the close integration of IT and OT, the new architecture enables the flexible adaptation of manufacturing processes, improves real-time transparency, and lays the foundation for sustainable, paperless workflows. This success story demonstrates how, through the targeted use of selected SDM building blocks, a scalable and modern production approach can be implemented that sustainably enhances transparency, flexibility and digital end-to-end consistency. ElringKlinger thus joins the ranks of MHP success stories that demonstrate how data-driven technologies can sustainably transform production systems and pave the way for greater efficiency and future viability.

Success Story on page 64

ElringKlinger

ElringKlinger – On the path to a software-defined factory
Achieving flexible, scalable, and future-proof production with MHP

Explore more customer success stories

Both partner and rival: Why Chinese companies are so successful – and what drives China's speed

Interview

An interview with Bernd Reitmeier, CEO of Start-up Factory China, who has witnessed China's development over the last 27 years, moving from cheap labor to high-quality production and fast-cycle innovation. Questions: Niclas Maasackers and Xu Zhao

Startup Factory China is a business incubator based in Kunshan that supports European small and medium-sized enterprises (SMEs) seeking assembly or production facilities, repair workshops, or application centers in China as part of their international expansion. Since its founding in 2011, Startup Factory has evolved from a simple idea into a fully developed model combining both shared infrastructure and professional services. Located just outside Shanghai, an experienced German-Chinese management team, led by Bernd Reitmeier, currently oversees the operations of 45 European subsidiaries employing around 500 people. The campus has grown through three construction phases and now spans 40,000 m^2 of office and production space. Alongside flexible rental workshops, Startup Factory provides a comprehensive service package covering central overhead functions, allowing customers to fully focus on production and business development.

Niclas Maasackers (MHP):
After completing your studies in industrial engineering at the Technical University of Berlin, how did you begin your business career?

Bernd Reitmeier (Startup Factory):
After earning my master's degree, I moved to China in 1998 and worked for the German Chamber of Commerce until 2010. At that time, we had around 150 employees, and much of our work involved market entry, investment, sourcing, and sales in China. With my technical background, I developed the idea of creating an incubator. The aim was not only to support German companies but also SMEs from across Europe that required a production base in China. We started from scratch without any clients, and today I believe we have become the largest German business incubator worldwide.

Niclas Maasackers:
How would you describe your incubator's business model?

Bernd Reitmeier:
In China, we focus on manufacturing sites, some of which are quite small. Altogether, we employ about 500 people across the companies based here. Some firms have only 10 to 20 employees, yet we generate revenues between € 9–12 million. Our concept has two pillars: hardware and software. On the hardware side, we provide fully scalable workshops ranging from 200 to 2,000 m^2 that can be adjusted up or down depending on business needs. This includes IT infrastructure, measuring equipment, forklifts, central warehousing, and MES – essentially anything that can be shared. On the software side, we continuously develop new services, from flexible staffing to joint training initiatives.

Niclas Maasackers:
And in addition, you manage the companies' operations?

Bernd Reitmeier:
Exactly. We call that the software element – our management services. We handle finance, HR, and provide technical teams, including auditors, since many of our clients face weekly audits. Our team of 50 employees works closely with the companies every day. This model is unique worldwide. We are highly operations-focused: We know most of our clients' customers who visit the site, support during audits, take part in monthly client meetings, and handle compliance, government relations, and facility management.

Niclas Maasackers:
Who are your typical clients?

Bernd Reitmeier:
Most are traditional, family-owned businesses, often over a century old, with 500 to 1,000 employees. We don't usually deal with start-ups. About half of our clients are connected to the automotive industry in some way.

Xu Zhao (MHP):
In your experience, what drives German companies – particularly in the automotive sector – to establish a presence in China?

Bernd Reitmeier:
There are about 6,500 German companies in China. Most are here for the domestic market rather than for exports – less than 5 percent export from China. Typically, a company enters China because one or two key customers require local production at a certain scale.

In the last five years, innovation has also become a major factor. Many of our clients rely on Chinese suppliers for cutting-edge materials or benefit from the speed of innovation processes in China. A presence here also provides access to new markets that don't exist in Europe.

That said, China strongly encourages local production, since it brings in foreign technology and strengthens domestic competitors. Automotive was the first industry to localize, and now we are seeing the same in medical technology and beyond.

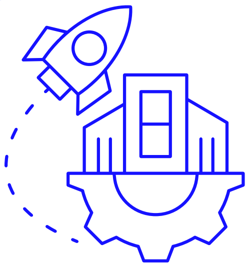
Niclas Maasackers:
What requirements must companies meet to operate successfully in China?

Bernd Reitmeier:
To participate in the Chinese market, you need local manufacturing. A sales office alone is not enough. For example, our two medical equipment clients must produce in China in order to qualify for public hospital tenders.

This is very different from the American model. U.S. firms often produce in China to export back home, using Mexico as their first choice for low-cost production. European SMEs typically use Eastern Europe – Bulgaria, Romania, or now Albania – because it's far easier than China. But companies that do enter China do so to compete locally.

Xu Zhao:
How do you see the role of Chinese companies in Industry 4.0 – mainly as users or also as innovators?

Bernd Reitmeier:
The "smart factory" concept became prominent about seven years ago, supported by



"We started from scratch without any clients, and today I believe we have become the largest German business incubator worldwide."

Bernd Reitmeier
CEO of Startup Factory China

China's "Made in 2025" plan, which aims to create global leaders across industries. At first, China was a user of IIoT. Over the last five years, it has become an innovator. Some of our automation clients are now European market leaders.

In AI, China is close to the U.S., though not quite at the same level. But if China decides to dominate semiconductors, I have no doubt they eventually will – perhaps after several failed attempts, but persistence pays off. According to research from Harvard's Kennedy Institute, China already leads in 28 of 37 innovative industries worldwide.

Xu Zhao:
What explains this innovation leadership?

Bernd Reitmeier:
It's a mix of strong government support and China's entrepreneurial spirit. The government shapes and controls industries while also tolerating high failure rates – 50 percent of companies may disappear, but the survivors thrive. Look at the solar industry: completely different players dominate today compared to 15 years ago. The fierce competition drives constant improvement.

Niclas Maasackers:
What other success factors support IIoT in China?

Bernd Reitmeier:
Data access is much easier than in Europe. Testing new systems or environments is straightforward – employees accept workplace cameras, and there are no unions. This creates an ideal environment to experiment with IIoT solutions, even for smaller firms.

Xu Zhao:
So China has the perfect conditions to innovate quickly?

Bernd Reitmeier:
People often say China is fast, but I think Europe has simply slowed down. I spend half my time in Europe and half in China or India, and the contrast is striking. Europe's business climate is no longer entrepreneurial.

China also embraces risk. Take Xiaomi: It began as a phone maker, then expanded into electronics and now cars. Which European company would dare to do that? Chinese entrepreneurs borrow money, leverage government ties, and seize opportunities. It's this risk appetite combined with entrepreneurship that fuels their progress.

Niclas Maasackers:
Given this, what do you see for the future of the automotive industry?

Bernd Reitmeier:
I believe we will soon see German-Chinese OEM joint ventures in Europe. Imagine Volkswagen partnering with SAIC to produce new models in Saxony or Braunschweig, using idle facilities. That would have been unthinkable five years ago, but innovation and leadership dynamics have shifted dramatically.

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2. Study findings

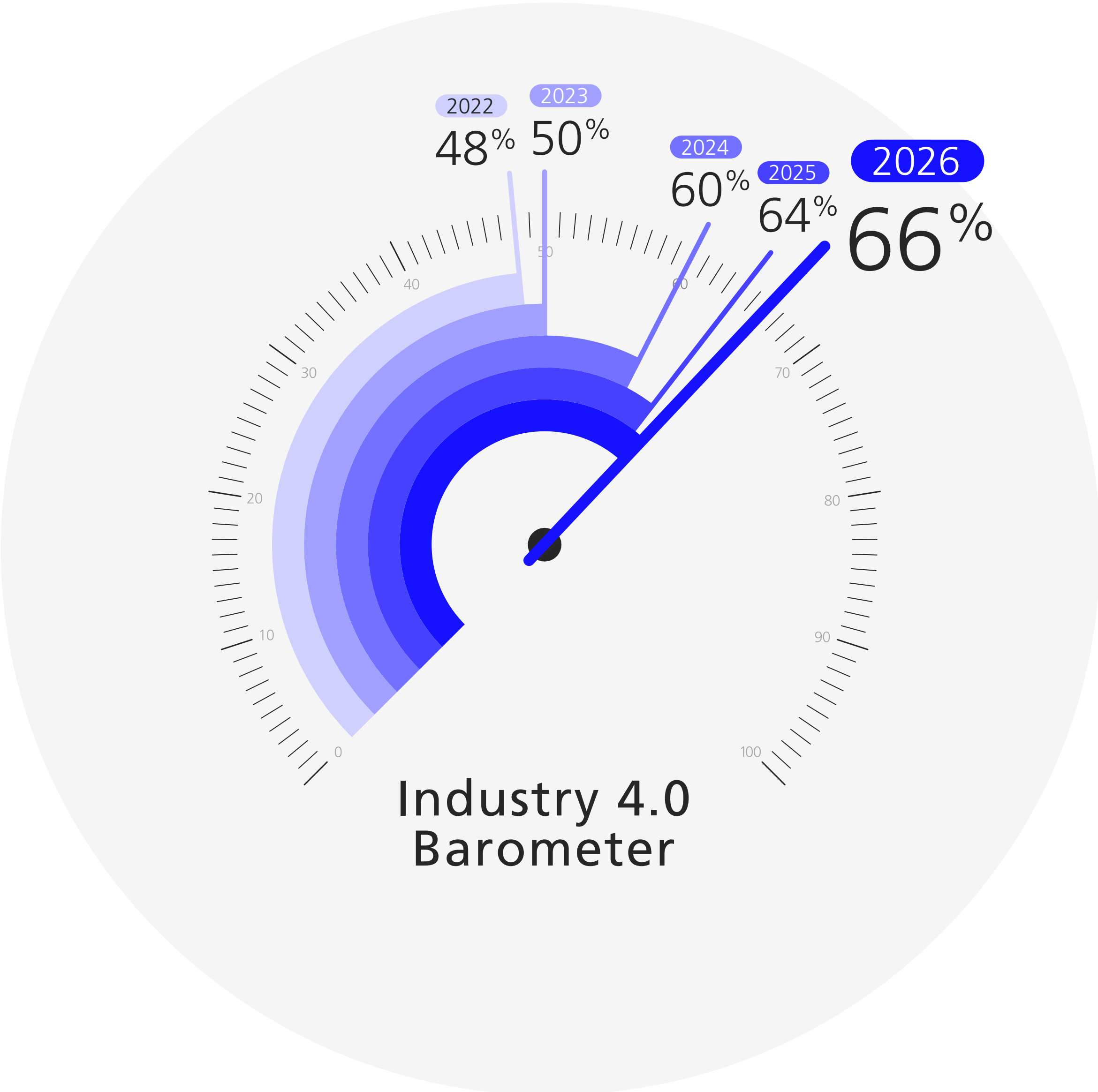


Fig. 5.1: Comparison of the overall barometer over the years

At the beginning of the chapter, an overview of the current status of Industry 4.0 is provided, supplemented by an analysis of the results in the clusters of Technology, IT Integration, Strategy and Goals, and Obstacles. Subsequently, the findings relating to the specific section, which this year focuses on the topic of Software-Defined Manufacturing, are presented. Finally, the role of the Chief Information Officer (CIO) and its significance for Industry 4.0 activities are analyzed in greater depth. This chapter thus provides a structured framework for interpreting and discussing the study's findings.

2.1. Status quo of Industry 4.0

Industrial manufacturing continues to undergo transformation, characterized by increasing digitalization, connectivity, and data-driven production control. Technologies such as the digital twin, artificial intelligence, and the IoT are becoming an integral part of production and supply chains and are serving as key drivers of efficiency, transparency, and operational adaptability.

Companies are increasingly relying on data-driven approaches to support operational processes and strategic decisions. In the process, priorities and objectives are shifting: In addition to increased efficiency, quality, flexibility, and market development are gaining strategic importance. At the same time, challenges remain, for example in establishing organizational prerequisites, in addressing the shortage of skilled workers, and in ensuring the return on investment.

This year's Industry 4.0 Barometer highlights progress and provides a concise overview of the industry's current state, with the aim of giving readers a well-founded picture of the latest developments.

2.1.1 Overall Barometer Score

Each year, the overall barometer score reflects progress in the key areas of Technology, IT Integration, Strategy and Goals, as well as Obstacles. The developments in these barometer scores are analyzed for the period from 2022 to 2026, and the scores are compared with one another. The overall barometer score is calculated as the average of the barometer scores for the four topic clusters for each year. The barometer scores for the Obstacles cluster were inverted to show the opposite scale and thus adequately reflect the progress made in overcoming these hurdles. The Strategy and Goals topic cluster is not included in this calculation, as the available data cannot be converted into a mathematically comparable barometer score.

This year, the study places greater emphasis on the context of Software-Defined Manufacturing (SDM). To this end, the Technology cluster was expanded to include the additional dimension of Artificial Intelligence (AI), which is now also factored into the overall barometer score. As a result, the Technology topic cluster now encompasses the areas of supply chain transparency, digital twin, automation and autonomous systems, and AI.

Development for the Technology cluster over the years

Technology

Supply Chain Transparency

2022	41%
2023	47%
2024	57%
2025	62%
2026	67%

Digital Twin

2022	35%
2023	38%
2024	50%
2025	58%
2026	65%

Automation & Autonomous Systems

2022	41%
2023	44%
2024	52%
2025	57%
2026	63%

Artificial Intelligence

2022	
2023	
2024	
2025	
2026	64%

Development for the IT Integration cluster over the years

IT Integration

IT Architecture

2022	57%
2023	60%
2024	71%
2025	75%
2026	78%

IT Security

2022	63%
2023	66%
2024	75%
2025	78%
2026	79%

Scaling of IT Systems

2022	55%
2023	57%
2024	70%
2025	73%
2026	76%

Data Analysis Capability

2022	49%
2023	59%
2024	69%
2025	71%
2026	75%

Development for the Obstacles cluster over the years

Obstacles

Resources

2022	56%
2023	60%
2024	52%
2025	46%
2026	53%

Prerequisites

2022	56%
2023	57%
2024	51%
2025	48%
2026	54%

Fig. 5.2: Comparison of the overall barometer over the years (by topic cluster)

Artificial intelligence supports the intelligent control of production processes, the optimization of machine and system parameters, and data-driven decision-making processes. In the IT Integration cluster, the focus continues to be on IT architecture, IT security, the scaling of IT systems, and data analytics capabilities, which are essential for implementing a software-driven manufacturing approach. The Obstacles Cluster examines key resources and prerequisites for the implementation of SDM technologies. It identifies both barriers – such as a shortage of skilled workers, capacity constraints, supply chain issues, and uncertainties regarding return on investment (ROI) – and enabling factors, such as the elimination of data silos and the management of legacy systems.

The overall barometer score is calculated as the average of the barometer scores for the topic clusters (Figure 5.2) for the year 2026, including India and Mexico, which are being considered for the first time. The results indicate a positive trend in the examined topic areas over the entire analysis period. From 2022 to 2026, the overall barometer score rises significantly from 48 percent to 66 percent, which corresponds to a relative increase of 39 percent (Figure 5.1). The survey results below provide a detailed look at this increase within the individual clusters.

Development of the overall barometer score in an international comparison

In addition to the overall trend over time, an international comparison of the overall barometer scores for the years 2024 to 2026 reveals significant differences between the countries examined (Figure 5.3).

In 2024, China leads the way at 69 percent, followed by the U.S. at 61 percent. The UK (55 percent) and the DACH region (52 percent) are at a similar, but lower, level.

In 2025, all of the regions under review show increases. The U.S. increases its score to s 66 percent, thereby solidifying its position among the top performers. At 69 percent, China remains stable at a high level. The United Kingdom is showing above-average momentum, with an increase to 64 percent. The DACH region also improves to 57 percent, but still lags behind in comparison.

This trend continues in 2026. At 72 percent, China achieves the highest overall barometer score among the countries compared. The U.S. follow with 69 percent. Newly included in the analysis are India (68 percent) and Mexico (67 percent), which immediately record high values and position themselves in the upper mid-range. The UK stands at 62 percent, slightly below its previous-year value, while the DACH region remains stable at 57 percent.

Overall, the international comparison shows that China and the U.S., in particular, have established a leading role over the entire period. While the UK has shown dynamic growth, with occasional fluctuations, the DACH region, despite improvements, continues to lag structurally behind the international leaders. The countries analyzed here for the first time, India and Mexico, underscore the growing international relevance of Software-Defined Manufacturing and related technologies.

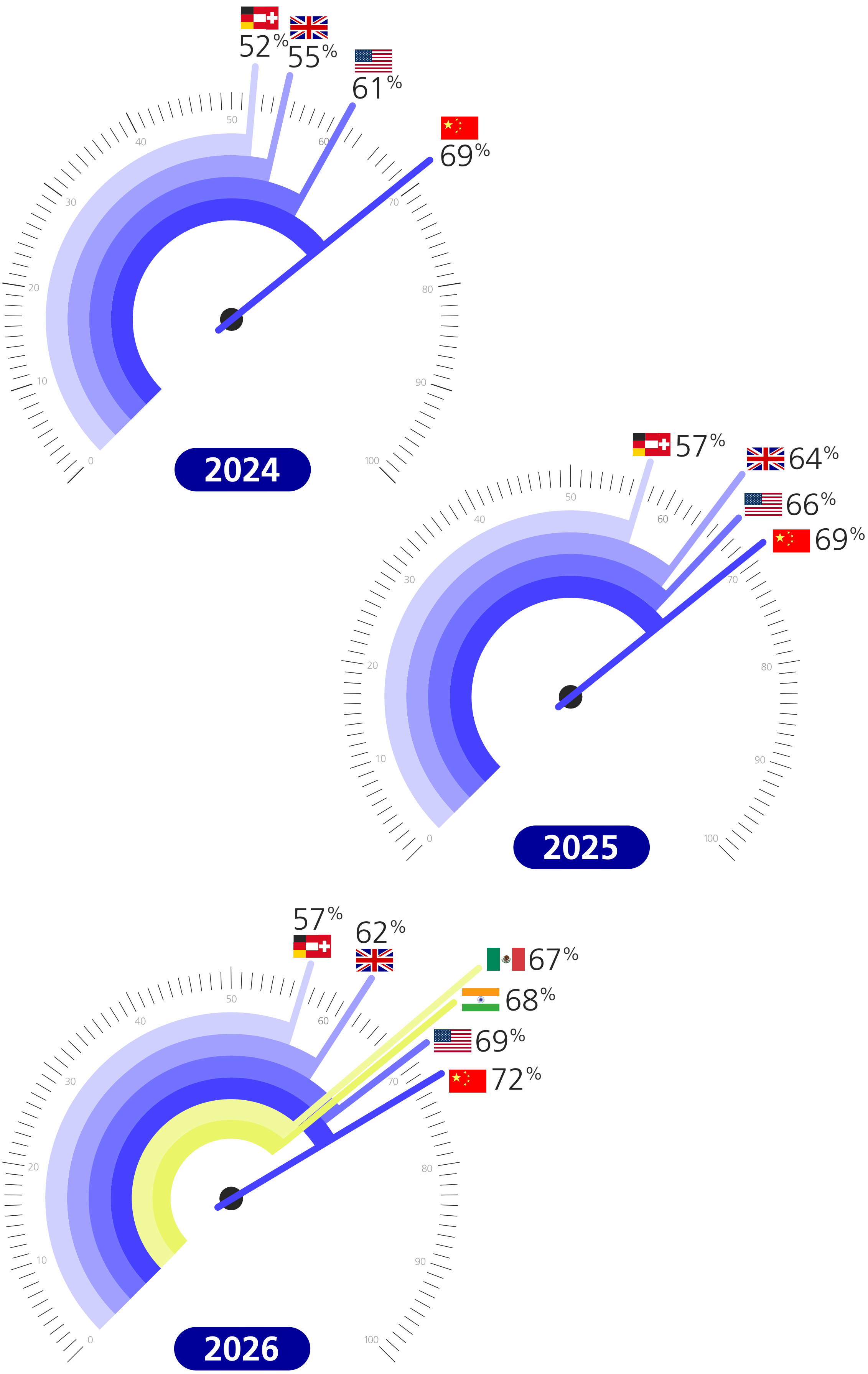


Fig. 5.3: Overall barometer score in international comparison

Supply Chain Transparency

This topic cluster examines the current state of operational traceability, i.e., the ability to track products and individual components along the value chain and actively control production processes, as well as the use of sensor-based systems for capturing and transmitting environmental and condition data in production, warehousing, and logistics. Precise location tracking and real-time information are growing in importance, especially in the context of Software-Defined Manufacturing, which enables increasingly data-driven and flexible control of production processes

Companies that can monitor their supply chains in real time not only increase their efficiency but also their resilience to market volatility and unforeseen disruptions. As a result, transparency is becoming a key tool for enhancing agility and resilience throughout the entire supply chain – and, consequently, companies are increasingly investing in related solutions.

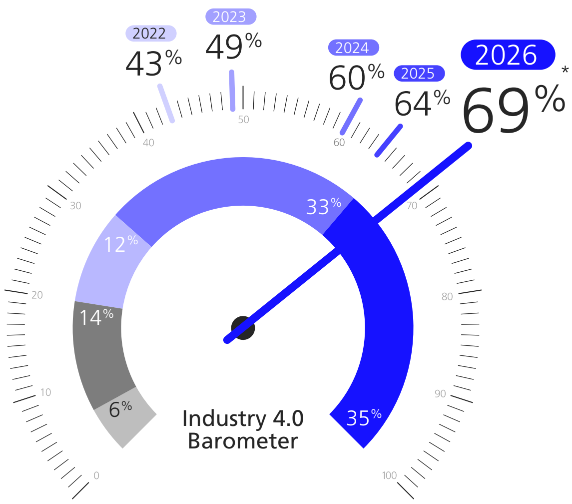
Precise tracking of products and resources is no longer a “nice-to-have” but is evolving into a strategic success factor.

In this year’s survey, 68 percent of respondents indicated that their company is already partially or fully capable of locating both individual components and end products. This represents an increase of eight percentage points compared to the previous year. The barometer score underscores this momentum: It rises from 60 percent in the 2024 barometer to 64 percent in 2025, reaching 69 percent in this year’s study – the highest score within the Technology topic cluster, as in the previous year. This continuous upward trend indicates that operational traceability is increasingly becoming a standard requirement.

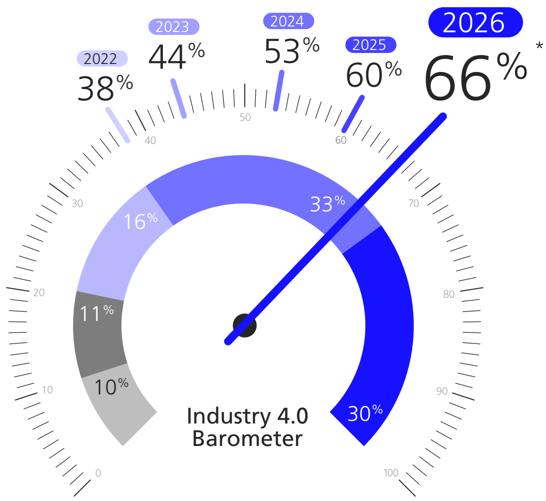
A similar picture emerges when it comes to sensors: 63 percent of respondents report that their plants and systems are partially or fully equipped with sensors that collect and transmit environmental parameters and condition data. This represents an increase of eight percentage points compared to the previous year. The barometer score rises even more sharply, from 53 percent in the 2024 barometer to 60 percent in 2025, reaching 66 percent in the current study (Figure 6). The increasing deployment of sensors may indicate that companies are implementing new manufacturing technologies, systems and processes – a possible sign that they are expanding into new markets or growth areas, as additional sensors are rarely required for existing systems and processes. They are usually installed only when new technologies, processes, or market requirements need to be monitored. Consequently, additional sensors often provide limited benefit in established systems. In summary, the data indicate that sensor deployment is becoming a key lever for data-driven production and logistics processes.

The international comparison, however, presents a much more nuanced picture. China occupies a leading position in traceability: 80 percent of respondents report that they are already partially or fully capable of tracking both individual components and end products. The U.S. follows in second place, with 77 percent. The mid-range is formed by the United Kingdom with 67 percent, and Mexico and India with 65 percent each. The DACH region lags behind at 53 percent, representing a 27-percentage-point gap to the frontrunner, China (Figure 7.1). A similar pattern can be observed in the area of sensors. Here, too, China leads with 74 percent, followed by the U.S. and India, where 68 percent of respondents report that their plants and systems are already partially or fully equipped with the relevant sensors. Mexico (61 percent) and the United Kingdom (58 percent) are again in the midfield, while the DACH region remains in last place at 49 percent (Figure 7.2).

Technological equipment along the entire value chain



At my company, all individual components of our products, as well as our end products, can be tracked along the entire value chain (from inbound logistics to production to customer service) (traceability).



Our facilities and systems in production, warehousing and logistics are equipped with sensors to record and transmit environmental parameters and condition data.

No deployment | Deployment planned | Ongoing practical tests | Partial deployment | Full deployment

Fig. 6: Technological equipment along the entire value chain / n – 1,206

* Barometer score: weighted arithmetic mean expressed as a percentage

At my company, all individual components of our products, as well as our end products, can be tracked along the entire value chain (from inbound logistics through production to customer service) (traceability).

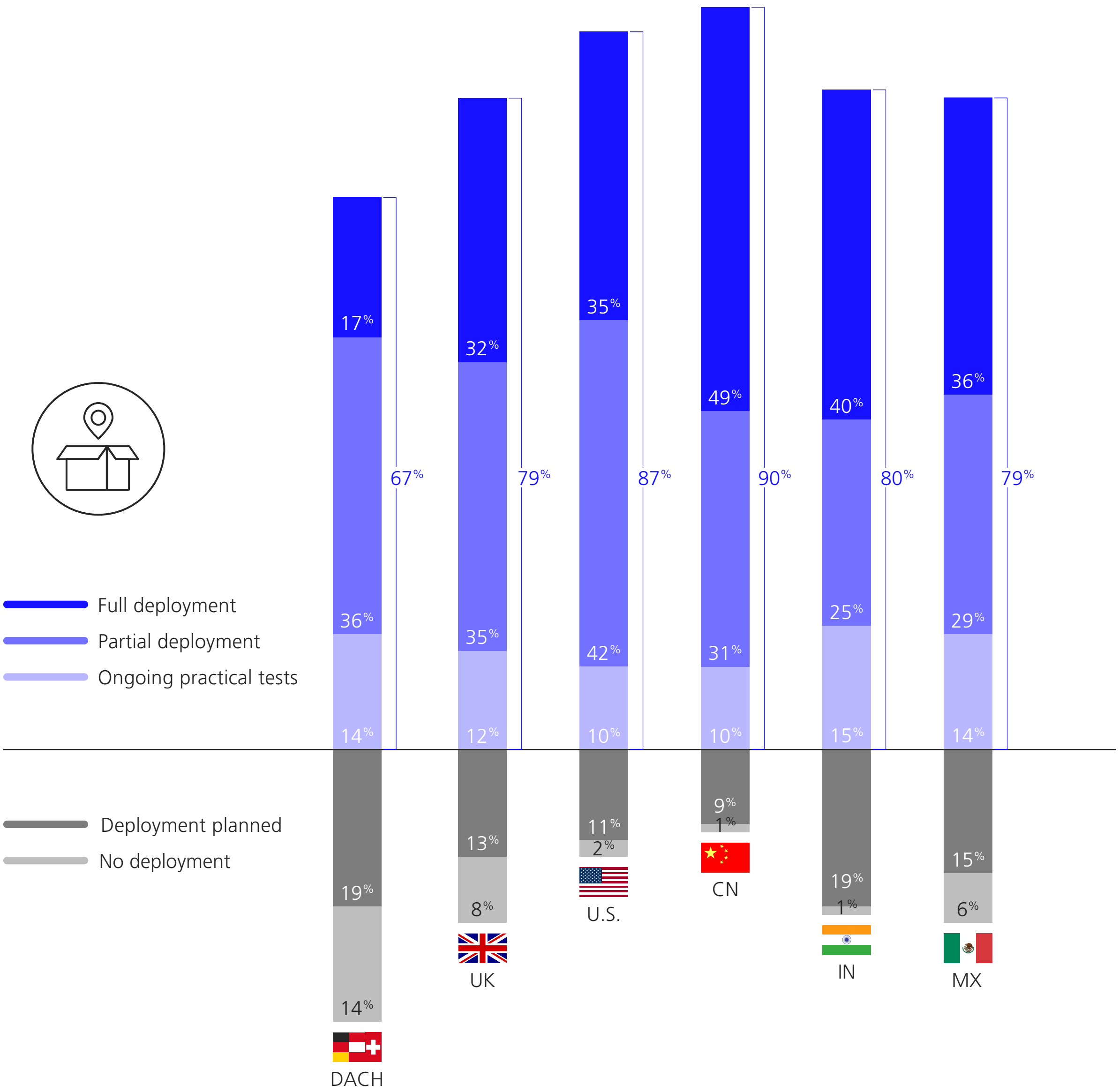


Fig. 7.1: Supply chain transparency by region
(product tracking across the entire value chain) / n – 1,206

Our facilities and systems in production, warehousing, and logistics are equipped with sensors to record and transmit environmental parameters and condition data.

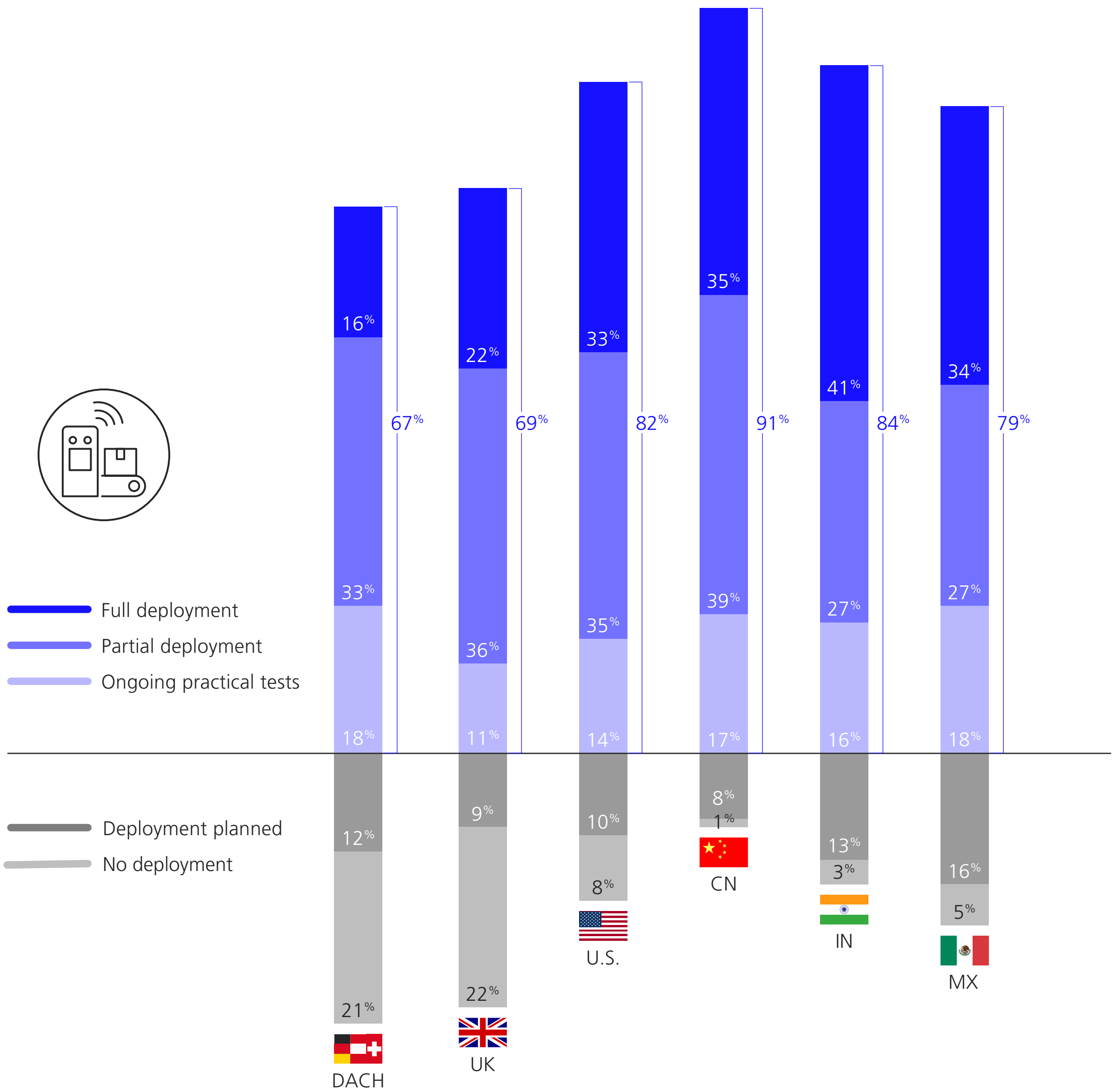
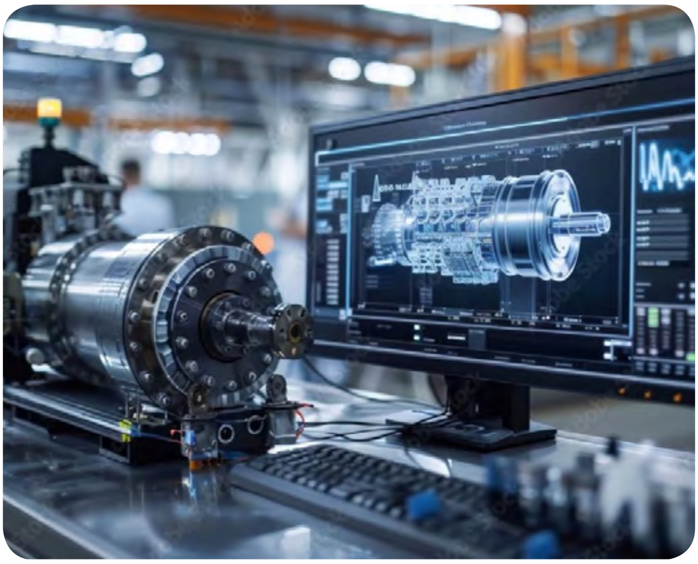


Fig. 7.2: Supply chain transparency by region
(equipping plants and systems with sensors) / n – 1,206

The observed differences can be attributed to several influencing factors. On the one hand, China and the U.S. exhibit a faster pace in implementing digital production and monitoring systems, indicating a higher willingness to invest and a more dynamic technology adoption. On the other hand, the gap of the DACH region can partly be explained by technical debt and established IT/OT landscapes: Companies there need to integrate existing systems and modernize older structures, which slows progress. At the same time, the DACH region faces regulatory pressure regarding traceability: The EU Digital Product Passport, planned for 2027, requires companies to provide product data for the circular economy and sustainability assessment. However, many companies currently do not have fully available data, so the new regulations are expected to drive the implementation of traceability in the future. Consequently, the DACH region must not only catch up in terms of operational traceability to remain competitive internationally, but also meet increasing regulatory requirements. Overall, the international comparison highlights the leading position of Asian markets in technological implementation as well as the challenges posed by legacy systems in European companies.

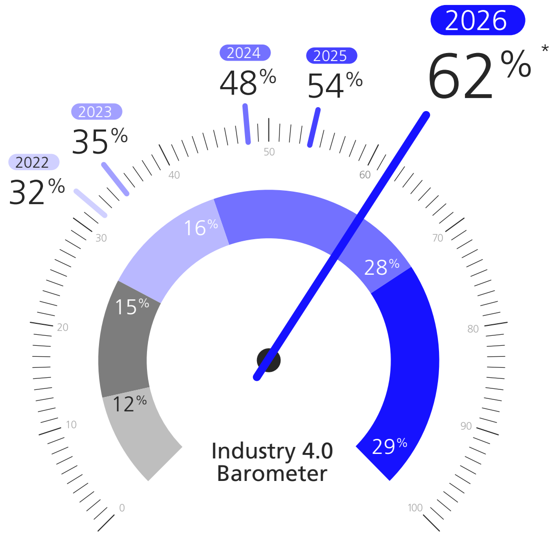


Digital Twin

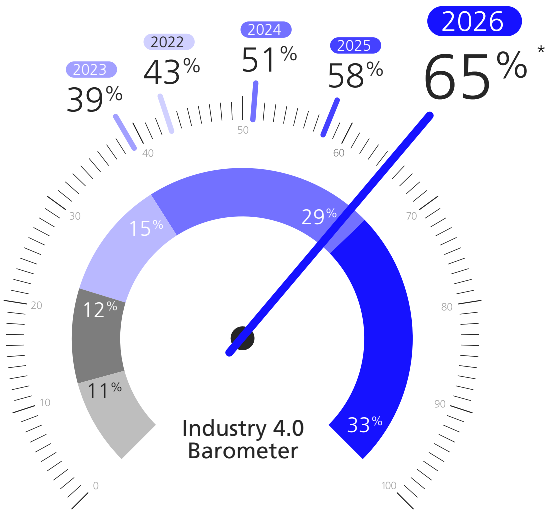
The willingness of companies to invest in the digitalization of their supply chains continues to increase significantly. This trend is particularly evident in the increasing use of digital twins, i.e., virtual representations of products, processes, and resources used for simulation, control, and optimization.

The barometer score for the use of digital twins in production facilities rises from 54 percent in 2025 to 62 percent in this year's study. For the use of digital twins in the context of products, the value increases from 58 to 65 percent, and in the context of logistics, it rises from 61 to 67 percent. Digital twins thus remain most widely adopted in logistics. Around 64 percent of respondents report using digital representations in logistics, either partially or fully (Figure 8). Particularly notable is the average annual growth rate over the past four years, which stands at 22.5 percent. This indicates that digital twins, especially in logistics, are spreading faster than any other technology surveyed.

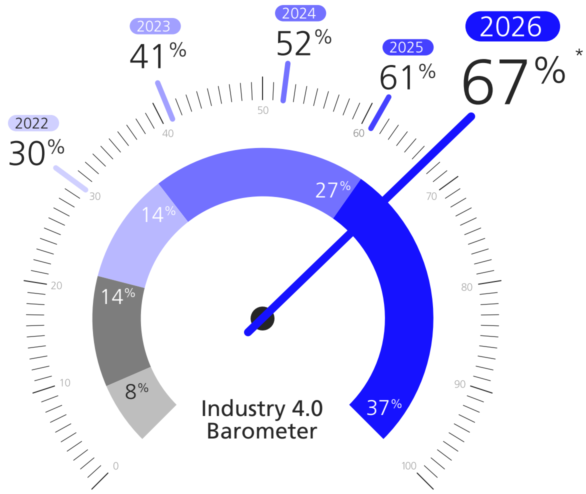
In my company, there is a digital replica that captures process and condition data for simulation, control, and optimization of ...



... our production facilities.



… our products.



… our entire logistics operations.

No deployment | Deployment planned | Ongoing practical tests | Partial deployment | Full deployment

Fig. 8: Adoption of the Digital Twin / n – 1,206

* Barometer score: weighted arithmetic mean expressed as a percentage

The high level of adoption in logistics shows that companies already clearly recognize the benefits of this technology in this area and are able to capitalize on them. Implementation is comparatively easier in this context because the technological hurdles are lower: Logistics processes can be more easily decoupled, allowing digital representations to be abstracted more readily. In production, on the other hand, the implementation of digital twins is more complex, as they must fulfill a wider range of functions and are more closely linked to machines and production facilities.

In particular, the use of digital twins for production and equipment optimization could be further expanded in the future, especially through standards such as the Asset Administration Shell (AAS), a structured digital representation of assets that enables faster implementation and facilitates interoperable data exchange.

Thus, while there is growing momentum in the use of digital twins across all sectors, an international comparison reveals differing speeds of implementation. In this regard, China clearly holds the leading position across all areas of application. Its lead is particularly pronounced in logistics: 84 percent of Chinese companies use digital twins in this area either partially or fully (Figure 9). Mexico follows with 74 percent, India with 68 percent, the U.S. with 61 percent, and the United Kingdom with 54 percent. The DACH region ranks last at 42 percent, meaning that only about half as many companies there use digital representations in logistics compared with China.

These differences can be attributed, among other factors, to differing digitalization strategies and investment dynamics. While China places a strong emphasis on data-driven technologies and process automation, the integration of digital twins in the DACH region often proceeds more gradually and is more closely aligned with existing structures. At the same time, a more conservative self-assessment by European companies could also further widen the gap. Overall, the international comparison shows that although the DACH region is making progress, it still lags behind in the global context in terms of the consistent implementation of digital twins.

Automation and Autonomous Systems

While the use of automation and autonomous systems still slightly lagged behind topics such as supply chain transparency and digital twin last year, the current survey indicates a clear upward trend.

Thus, 67 percent of participants report that they already use machine-to-machine (M2M) communication, i.e., forms of automated information exchange between plants, devices, and systems, either partially or fully (Figure 10). In practice, however, M2M communication rarely involves fully autonomous interactions. Instead, it typically refers to clearly defined, technically established applications such as docking procedures for automated guided vehicles (AGVs), higher-level control systems, process interlinking, as well as operations in manufacturing cells and production lines or transport systems. These forms of selective, rule-based communication are increasingly developing into the backbone of networked production and logistics processes.

In my company, there is a digital replica that captures process and condition data for simulation, control, and optimization of our entire logistics operations.

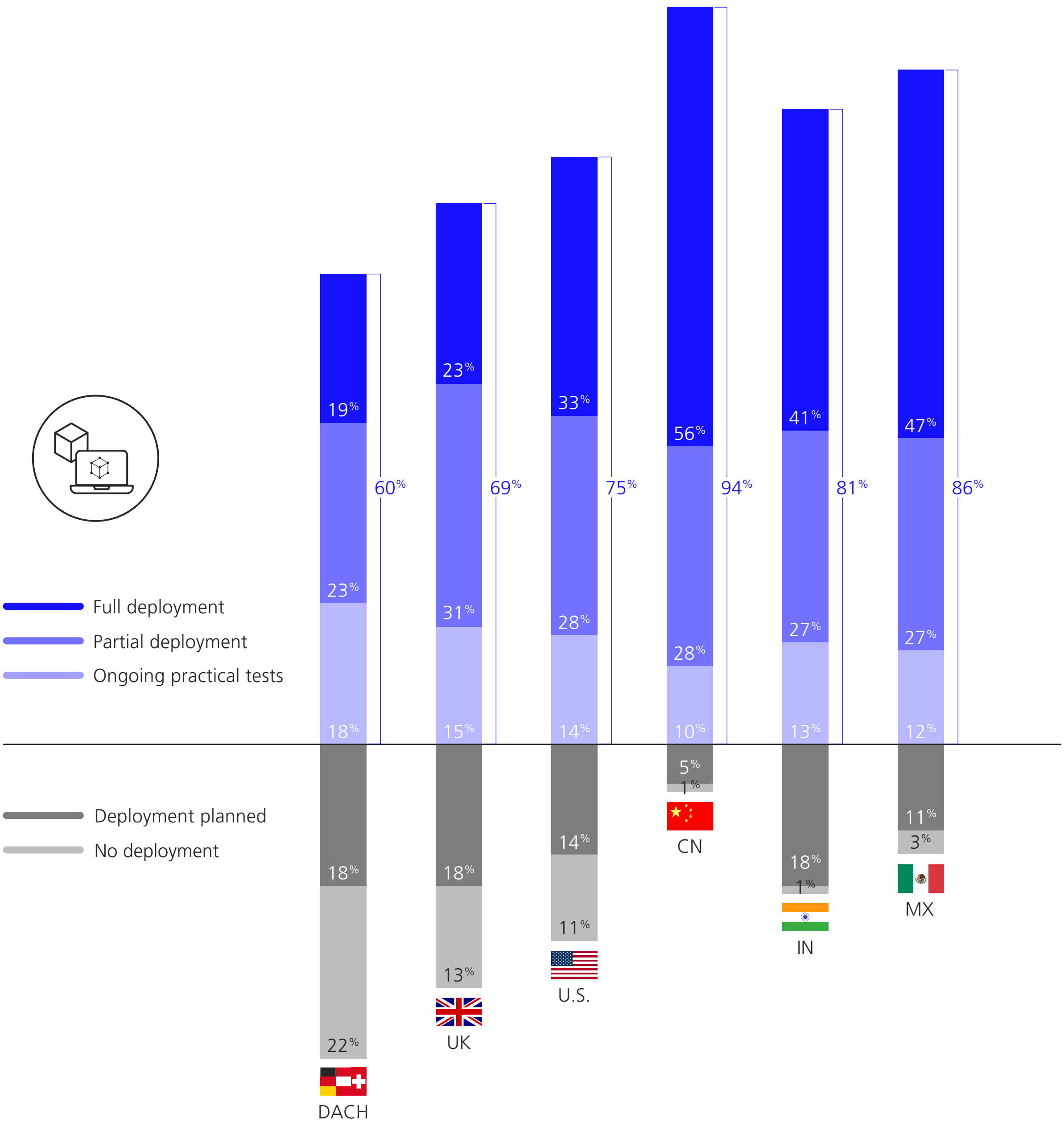
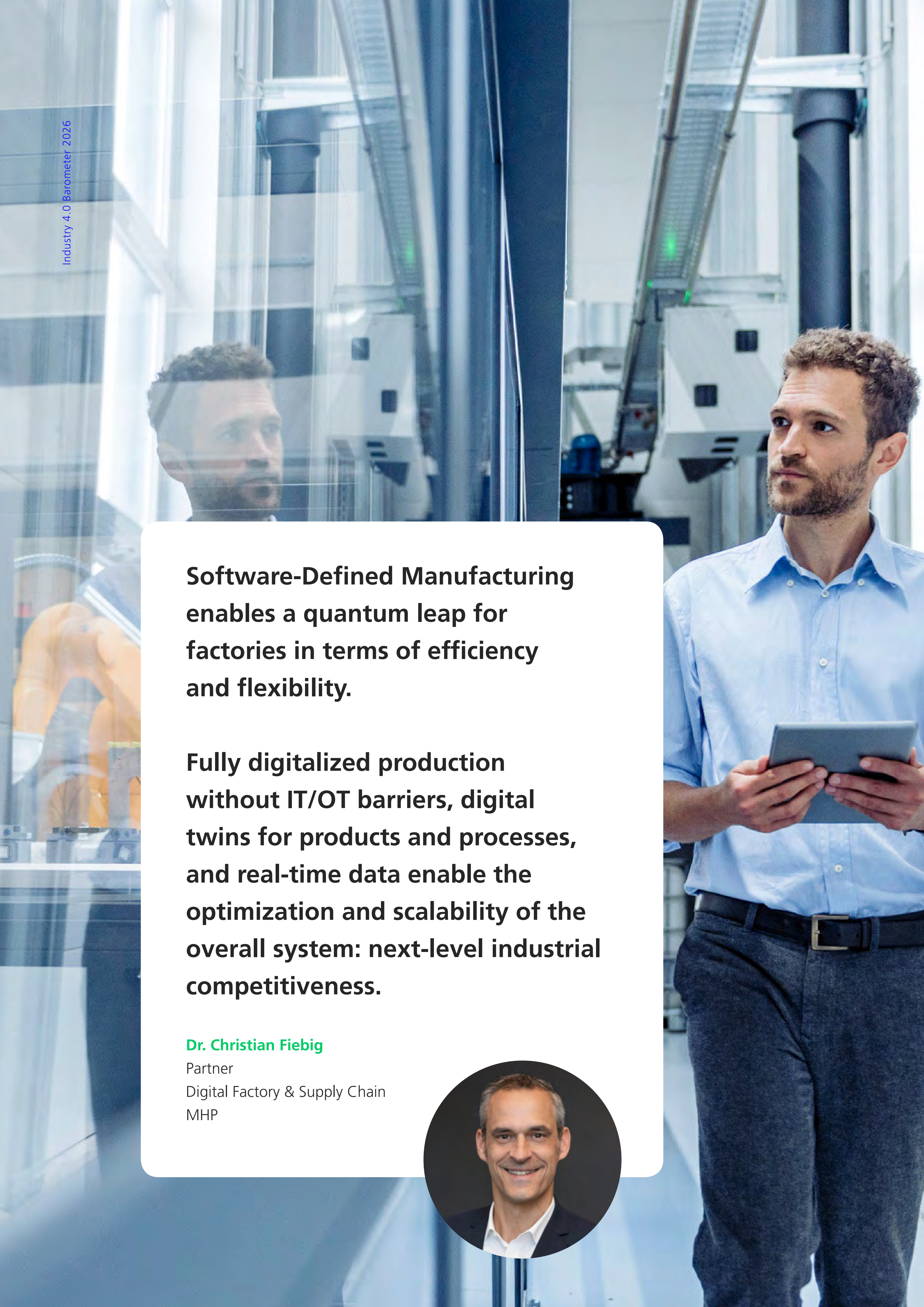


Fig. 9: Adoption of the Digital Twin by region / n – 1,206



Software-Defined Manufacturing enables a quantum leap for factories in terms of efficiency and flexibility.

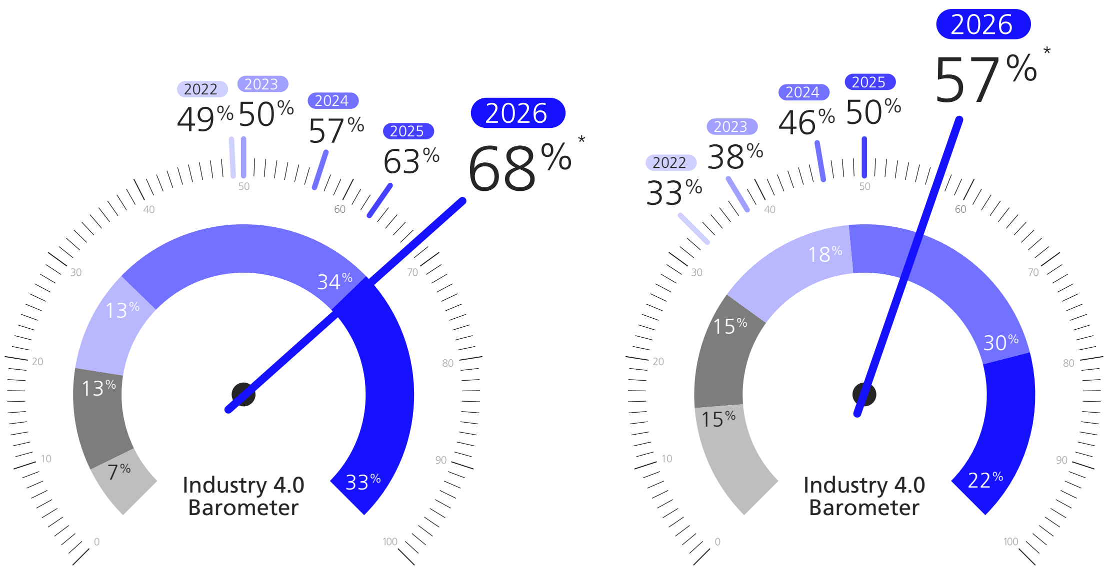
Fully digitalized production without IT/OT barriers, digital twins for products and processes, and real-time data enable the optimization and scalability of the overall system: next-level industrial competitiveness.

Dr. Christian Fiebig
Partner
Digital Factory & Supply Chain
MHP

This trend is reflected in the barometer score, which rises from 57 percent in 2024 to 63 percent in 2025, reaching 68 percent in this year's study. This indicates that companies are increasingly leveraging the benefits of connected machines to synchronize their processes and exchange data seamlessly between systems. M2M communication is thus becoming an ever more fundamental element of end-to-end automated value chains.

Although autonomous machines and robots are still less widely adopted, they show dynamic growth. Their use increases by 8 percentage points, from 44 percent last year to 52 percent in the current survey (Figure 10). This rise suggests that companies are gradually exploring the deployment of robotics in production environments. Particularly in areas such as material flow, order picking, and quality control, autonomous systems could make a decisive contribution in the coming years, helping to mitigate skilled labor shortages and unlock efficiency potential.

Maturity level of automation and autonomous systems



Our facilities, equipment, and systems exchange information automatically and independently in real time (machine-to-machine communication).

We use machines and robots that can act autonomously, self-regulate, or improve themselves (e.g., driverless transport systems).

No deployment | Deployment planned | Ongoing practical tests | Partial deployment | Full deployment

Fig. 10: Maturity level of automation and autonomous systems / n – 1,206

* Barometer score: weighted arithmetic mean expressed as a percentage

We use machines and robots that can act autonomously, self-regulate, or improve themselves (e.g., driverless transport systems).

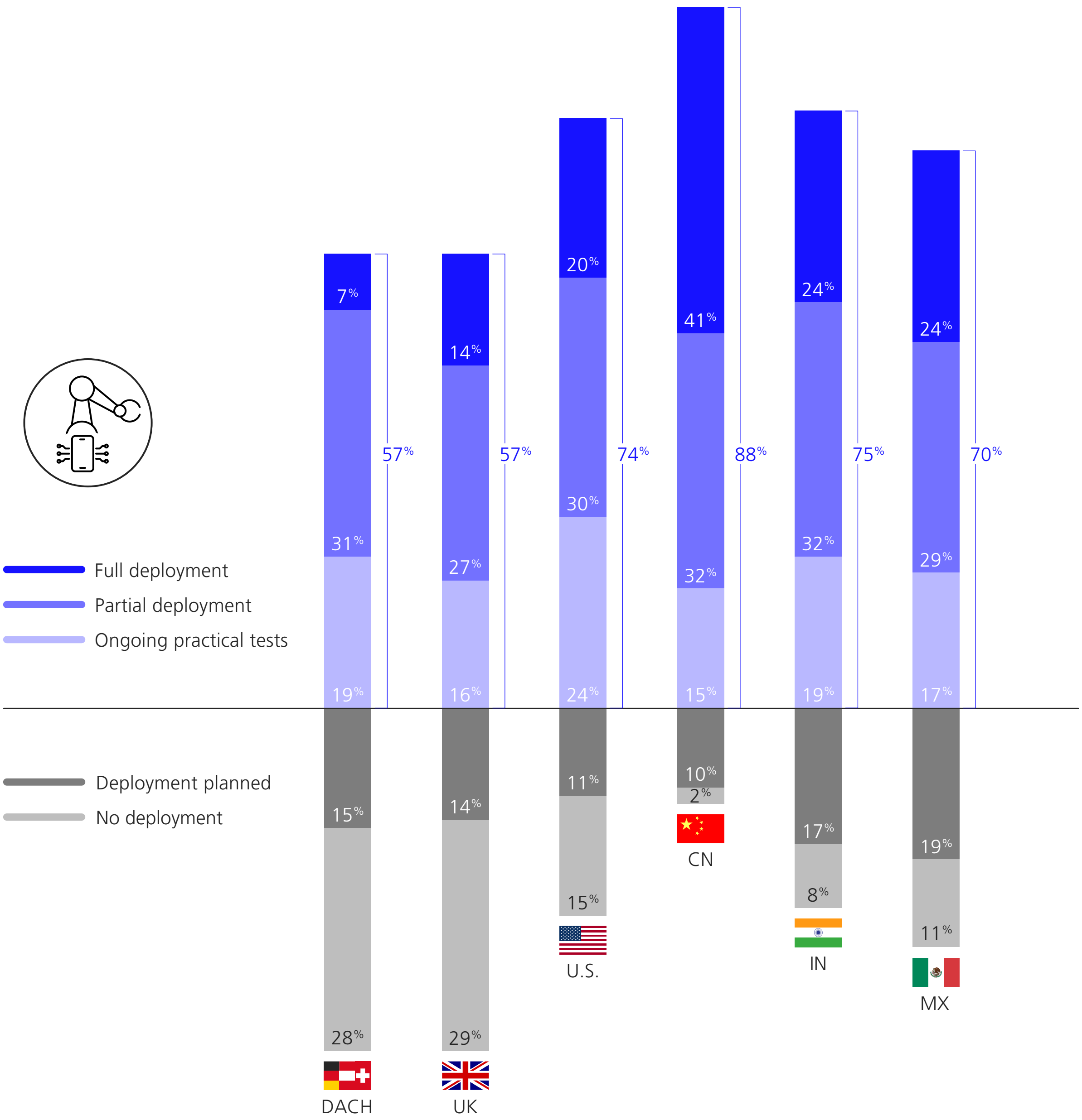


Fig. 11: Maturity level of automation and autonomous systems by region / n – 1,206

The results indicate that automation is no longer viewed solely as an isolated efficiency measure, but is increasingly embedded into a comprehensive digitalization strategy. The rising scores for M2M communication and autonomous systems suggest that companies are taking the next steps toward self-regulating, resilient production networks. This trend is likely to continue, laying the foundation for software-defined, increasingly autonomous manufacturing environments.

The global comparison shows that the progress towards higher levels of automation varies significantly by region. This is particularly evident in the area of autonomously operating machines and robots: China takes the lead, with 73 percent of participants reporting that they already use the respective technologies either partially or fully. This is followed by a broad mid-range with India (56 percent), Mexico (53 percent), and the U.S. (50 percent). The UK (41 percent) and the DACH region (38 percent) occupy the lower end (Figure 11).

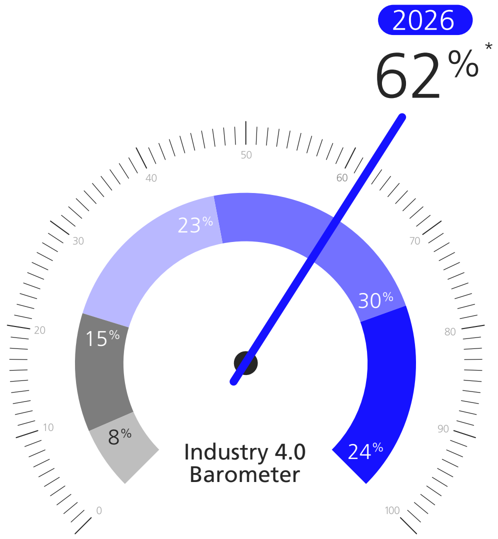
These differences can be attributed both to the technological penetration of the markets and to varying technological conditions and circumstances. While China has strategically invested in industrial process automation for years and government programs promote the adoption of robot-assisted systems, implementation in Western markets often proceeds more gradually and is more closely integrated with existing structures. In the DACH region, a strong focus on quality and safety also plays a role, which may lead to a more cautious adoption of autonomous systems. Overall, this international comparison underscores that, while automation is increasing worldwide, the pace and intensity of implementation strongly depend on regional conditions.

Artificial Intelligence

Against the backdrop of an evolving manufacturing landscape, in which data-driven decision-making and automated processes are steadily gaining importance, artificial intelligence (AI) has now been incorporated as a permanent component of this year's Industry 4.0 Barometer. The aim is to obtain an accurate picture of how companies currently use AI in the manufacturing context and what expectations they have for future developments.

To this end, participants were first asked to what extent their companies currently deploy solutions based on artificial intelligence that are integrated into manufacturing-related processes. 54 percent of respondents report that they use these technologies at least partially or fully, indicating an initial anchoring of AI solutions, but with clearly visible potential for further expansion. Considering only full deployment, the share drops to 24 percent, suggesting that AI is so far deeply integrated in relatively few companies (Figure 12).

Deployment of artificial intelligence in manufacturing-related processes



My company currently uses solutions based on artificial intelligence (AI) (e.g., predictive maintenance, anomaly detection, autonomous robots) in manufacturing-related processes.

No deployment | Deployment planned | Ongoing practical tests | Partial deployment | Full deployment

Fig. 12: Deployment of artificial intelligence in manufacturing-related processes / n – 1,206

* Barometer score: weighted arithmetic mean expressed as a percentage

Respondents also provided an assessment of the impact they expect AI to have on production over the next five years. 62 percent expect a significant to groundbreaking impact (Figure 13). The considerable gap between the current level of use and future expectations is referred to as the "AI hype gap": a typical phenomenon in which the projected importance of AI far exceeds the actual level of implementation. This discrepancy suggests that organizational, technological, or investment-related obstacles are slowing rapid implementation, even though the future potential of AI is rated highly across all industries.

The picture becomes particularly revealing in an international comparison. Regarding partial or full deployment of AI, participants from China lead with 71 percent, followed by India with 61 percent and the U.S. with 57 percent. Mexico (51 percent) and the United Kingdom (48 percent) occupy the mid-range, while the DACH region ranks last at 37 percent (Figure 14.1). These differences can be partly explained by the fact that countries

Assessment of the impact of AI over the next 5 years

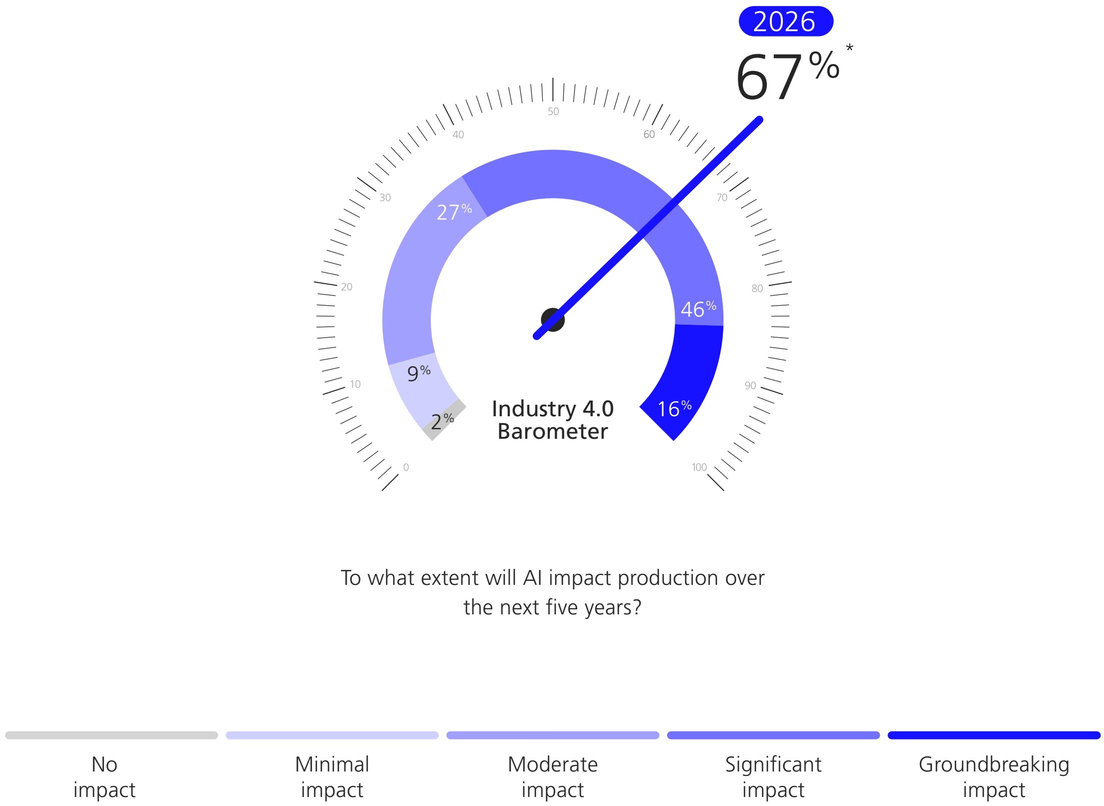


Fig. 13: Perceived impact of AI over the next 5 years / n – 1,206

* Barometer score: weighted arithmetic mean expressed as a percentage

such as China and India have invested heavily in digital infrastructures for years and exhibit a high level of technology acceptance, whereas companies in the DACH region traditionally act more cautiously and implement technological changes only after solid economic validation. In addition, government programs in China and a dynamic IT ecosystem in India promote early implementation.

Perceptions of the impact of AI over the next five years also vary significantly across countries. Respondents from the U.S. are the most optimistic, with 75 percent expecting significant or groundbreaking effects; India (69 percent), Mexico (67 percent), and UK (61 percent) occupy the mid-range, while China (52 percent) and the DACH region (51 percent) rate the potential more conservatively. The high expectations in the U.S. reflect the country's innovation and start-up culture, where new technologies are typically associated as having disruptive potential.

My company currently uses AI-based solutions (e.g., predictive maintenance, anomaly detection, autonomous robots) in manufacturing-related processes.

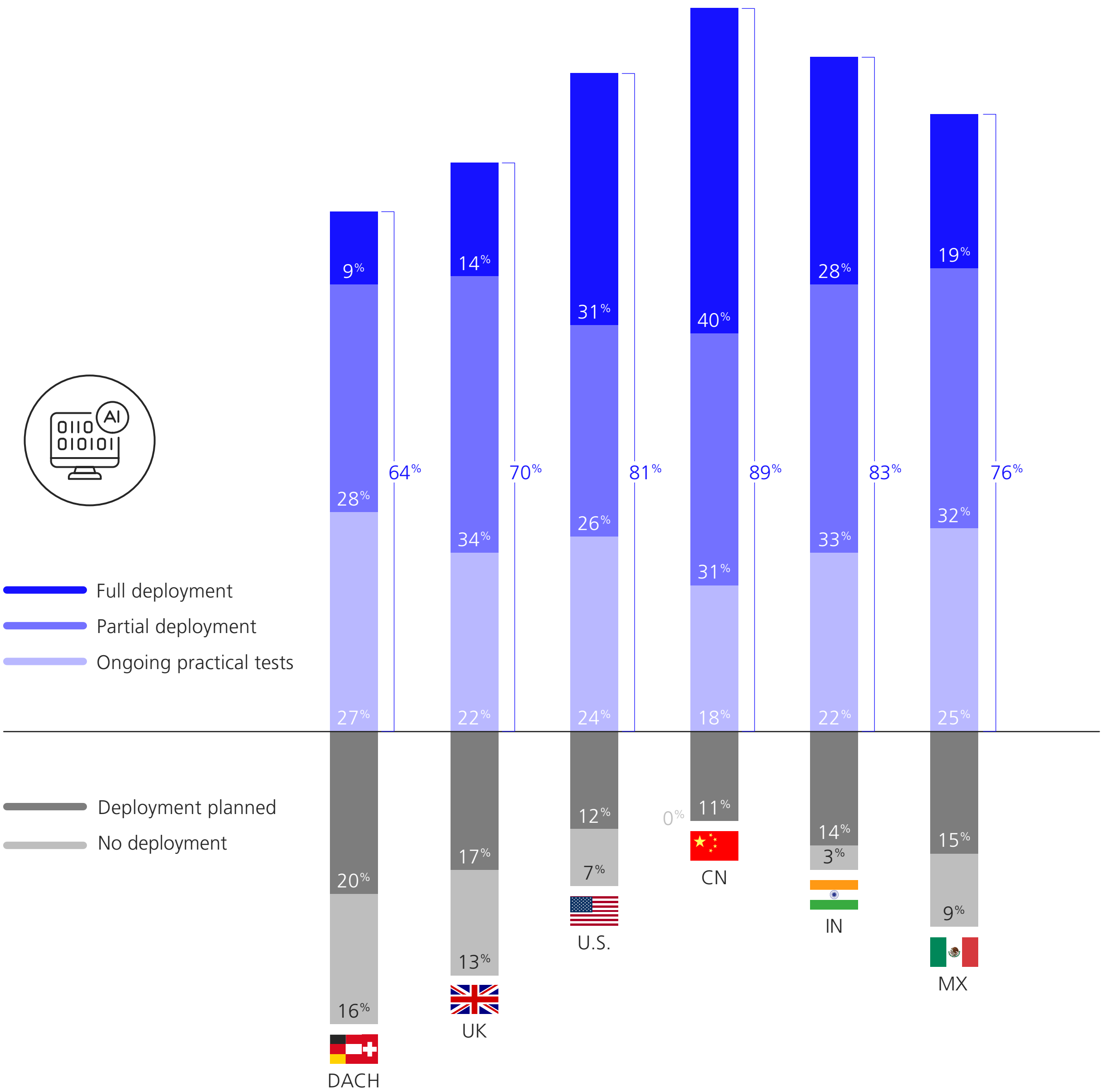


Fig. 14.1: Deployment of AI solutions in manufacturing-related processes by region / n – 1,206

To what extent will AI impact production over the next 5 years?

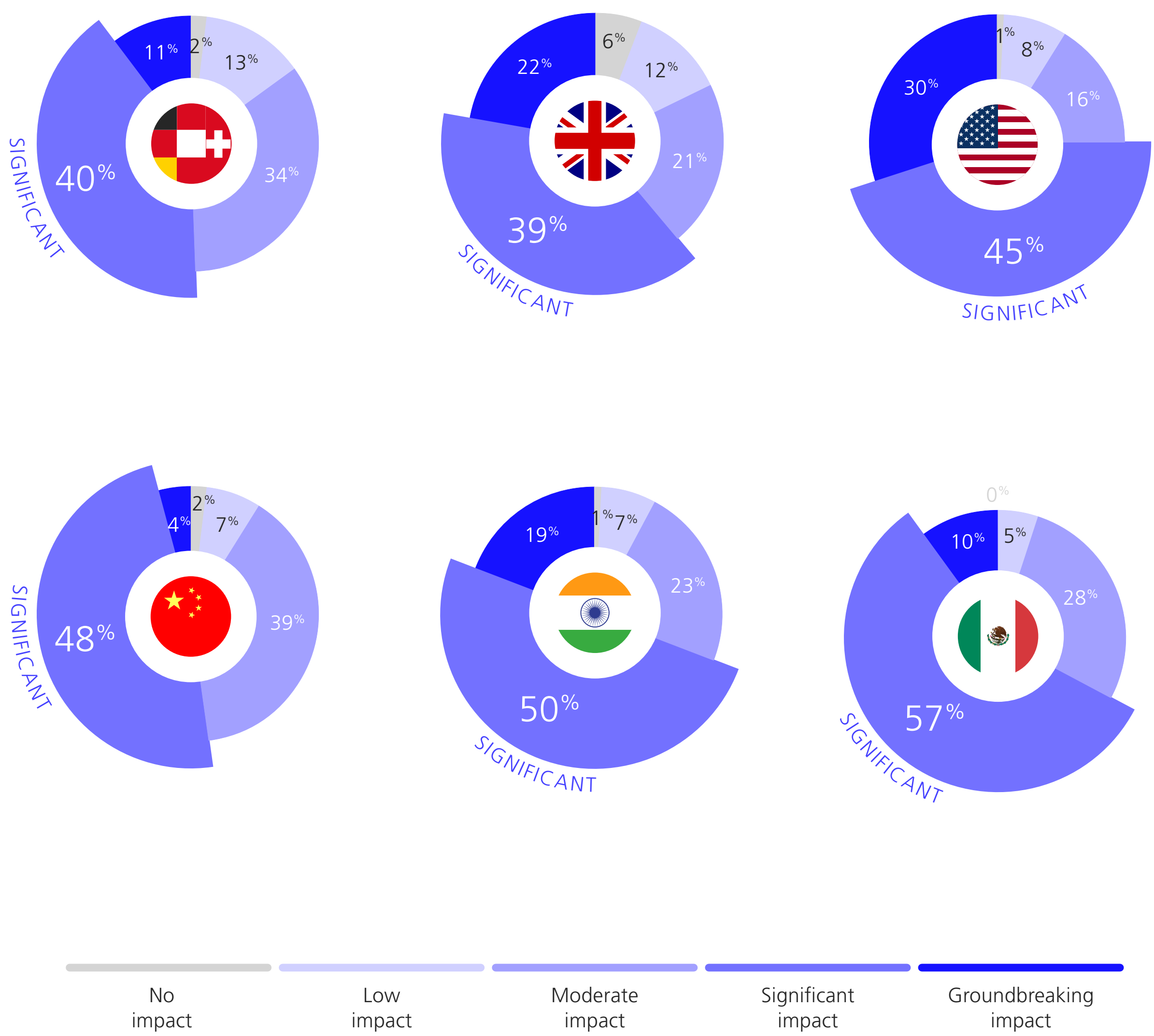


Fig. 14.2: Assessment of the impact of AI over the next 5 years by region / n – 1,206

The high expectations in the U.S. reflect the country's innovation and start-up culture, where new technologies are typically associated with disruptive potential, whereas China tends to make more conservative forecasts, indicating a more realistic assessment of AI's possible impact on production processes. Expectations in the DACH region can be interpreted similarly: Here, assessments are also more cautious until concrete use cases and efficiency gains become visible in industrial practice.

An even clearer picture emerges when looking at the highest response option, "groundbreaking impact." 30 percent of respondents from the U.S. chose this option – the highest value by far – highlighting the traditionally strong future- and technology-oriented mindset in the American market. In China, by contrast, only 4 percent chose this option, again illustrating that the potential of AI is viewed more conservatively there and less as a radically transformative force (Figure 14.2).

Overall, the results indicate that expectations and the levels of implementation vary widely worldwide and are shaped by both cultural and structural factors. The pronounced AI hype gap shows that, although companies have high expectations for AI, they are only partially translated into practical implementation. This underscores the need to deliberately expand competencies, investments, and organizational prerequisites in order to realize the anticipated potential of AI in industrial production in the future.

2.1.2 Topic Cluster 2 IT Integration

Data Analytics Capabilities

Companies are increasingly recognizing data-driven strategies across the entire value chain as a key competitive factor. Accordingly, this year's results show that progress in the area of data analytics capabilities is significantly greater than in the previous year. This development marks a turning point: away from isolated digitalization solutions toward a more software-centered approach to production management. In line with this, this year's focus topic is Software-Defined Manufacturing – an approach whose successful implementation requires strong data analytics capabilities.

Progress is particularly evident in technical infrastructure. This year, 80 percent of respondents rate their company's capabilities in this area as superior to those of their competitors, compared with 69 percent last year. The barometer score also rises from 72 to 78 percent, reaching the highest score among data analytics capabilities. This development demonstrates that companies are increasingly establishing the technological foundations necessary to take data-driven production control and software integration to a new level.

Significant progress is also evident in production processes with partially and fully automated decision-making. 70 percent of respondents now rate their capabilities in this area as superior, compared to only 59 percent the previous year. The barometer score confirms this upward trend: from 66 to 72 percent in the current study (Figure 15). In practice, however, this assessment primarily relates to automated evaluations of data flows and clearly defined decision-making logic – for example, threshold models or deterministic methods – rather than comprehensive AI- or ML-based (machine learning) process automation. Many companies have first prototypes, proofs of concept (PoCs), or stand-alone solutions in this area, which are subjectively perceived as an advantage over the competition. At the same time, the full integration of AI-based decision-making models into actual manufacturing processes remains significantly more challenging than in other business areas, due to physical dependencies, high data quality requirements, and necessary interoperability with machine manufacturers. Against this backdrop, it is understandable that this area, despite growth, still exhibits the lowest maturity level within data analytics capabilities.

The continuous expansion of modern infrastructures and the targeted development of expertise form the basis for systematically embedding automated decision-making processes. With an average annual growth rate of 19 percent, this area is among the fastest-growing across all fields surveyed. This highlights that companies are in the midst of transitioning to the software-defined factory, a production system primarily controlled by intelligent software architectures.

However, when compared internationally, the results clearly show that the development of data analytics capabilities varies greatly by region. Across all areas surveyed , India takes the lead, usually closely followed by China and Mexico. This lead is particularly evident in terms of capabilities related to production processes with partially and fully automated decisions: 84 percent of respondents from India rate their capabilities in this area as superior to those of their competitors, followed by China at 83 percent. Mexico (78 percent) and the U.S. (74 percent) occupy the middle ground, while the UK (59 percent) and the DACH region (43 percent) once again occupy the lower positions. This places the DACH region approximately 40 percentage points behind India (Figure 16).

84%

of respondents from India rate their expertise in production processes involving partially and fully automated decision-making as superior to that of their competitors.

Maturity level of data analytics capabilities

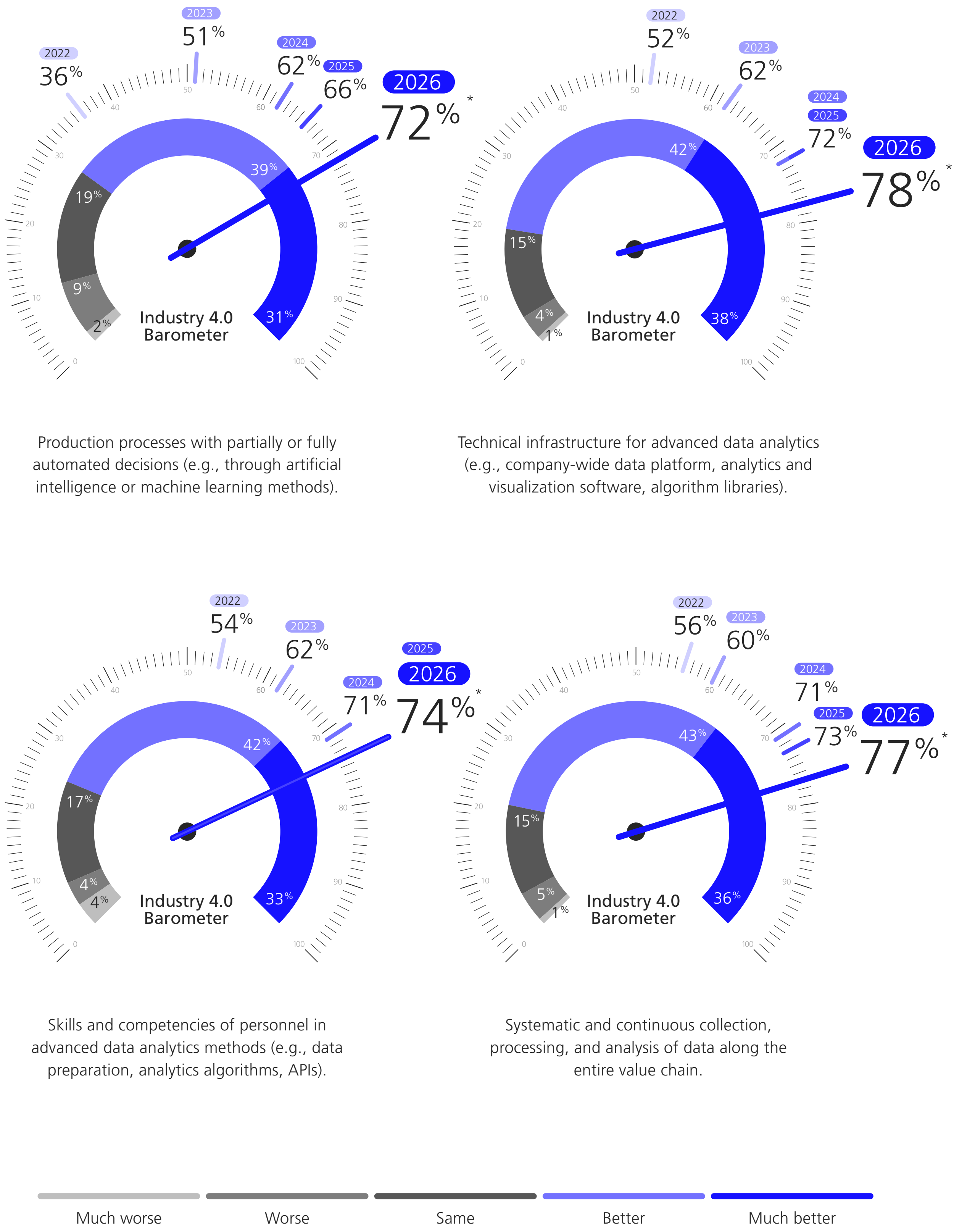


Fig. 15: Maturity level of data analytics capabilities / n – 1,206

* Barometer score: weighted arithmetic mean expressed as a percentage

Data analytics capabilities by region

Production processes with partially or fully automated decision-making (e.g., through artificial intelligence or machine learning methods)

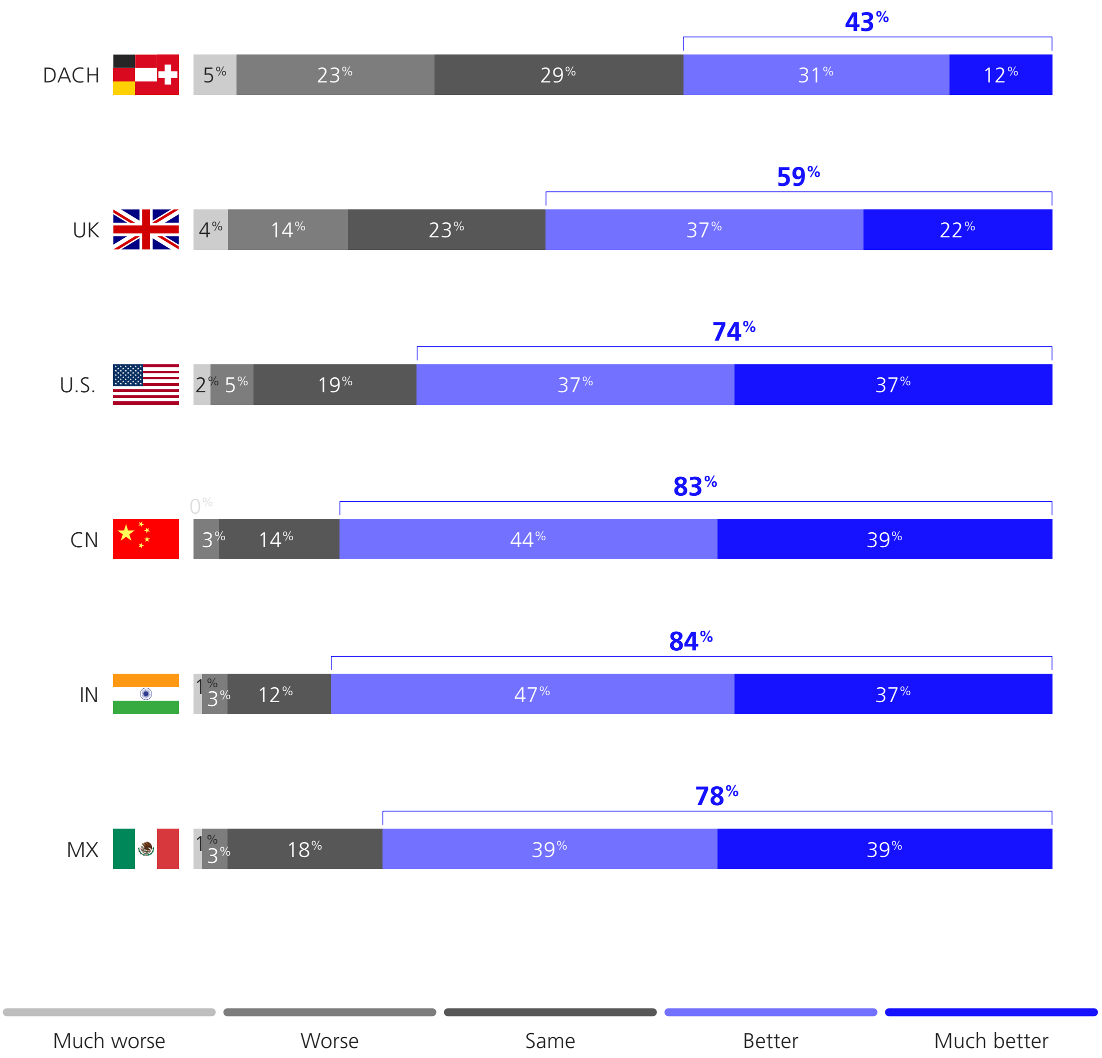


Fig. 16: Maturity level of data analytics capabilities by region / n – 1,206

This discrepancy can be partly explained by culturally different self-assessments – for example, the DACH region tends to adopt a more conservative evaluation of its own capabilities compared with the often stronger self-confidence observed internationally. It also reflects different structural starting points: In countries such as India and China, greenfield approaches, extensive digitalization programs, and the rapid shift to technology-driven production models significantly accelerate the development of capabilities. In contrast, the DACH region frequently develops its data-driven production systems on the basis of established and complex machinery and equipment landscapes, which makes the implementation of new decision-making procedures more challenging.

Overall, it is clear that the DACH region has a solid technological foundation but needs to expand its data analytics capabilities much more rapidly in order to remain internationally competitive. In particular, the transition from isolated solutions to comprehensive, software-defined production control requires strategic investments, targeted training initiatives, and a stronger integration of data-driven decision-making processes into day-to-day operations. Only in this way can the existing gap between the DACH region and the leading regions be closed in the long term.

IT Security

IT security is becoming increasingly important in companies and is widely regarded as an essential component of a reliable digital infrastructure. However, the current results show that progress in the individual areas of IT security varies.

Uniform authorization concepts for access to corporate data hold the top position among all surveyed IT security areas in 2025, with a barometer score of 80 percent. In this year's study, this value drops to 77 percent, marking the lowest position among all IT security topics. 85 percent of respondents report having such an authorization concept, compared with 86 percent in the previous year. This indicates that the practical implementation of uniform authorization systems is challenging and remains a lower priority compared with other security measures.

In contrast, there are signs of progress in the other two IT security areas. This is particularly evident when it comes to the influence of IT security management on key business decisions: 87 percent of respondents confirm this influence, up from 80 percent in 2025. The barometer score rises from 75 to 80 percent, demonstrating the growing importance of strategic IT security governance. Capabilities for defending against cyberattacks are also increasing, illustrating that companies are strengthening IT security both operationally and strategically.

The Barometer reveals a clear trend: IT security is noticeably gaining strategic importance. The new peak value confirms that cybersecurity is increasingly understood as a critical success factor and a prerequisite for innovation – not just an operational task.

At the same time, the overall environment is becoming more challenging: Attackers are operating in a more professional, organized, and automated manner, while regulations such as NIS-2 or the Cyber Resilience Act raise the requirements for transparency and accountability. Despite its increased importance, IT security remains an ongoing area of focus for many organizations that requires continuous attention.

Kevin Euler
Associated Partner Cyber Security (CYS)
MHP

Access to company data is regulated by a uniform authorization concept.

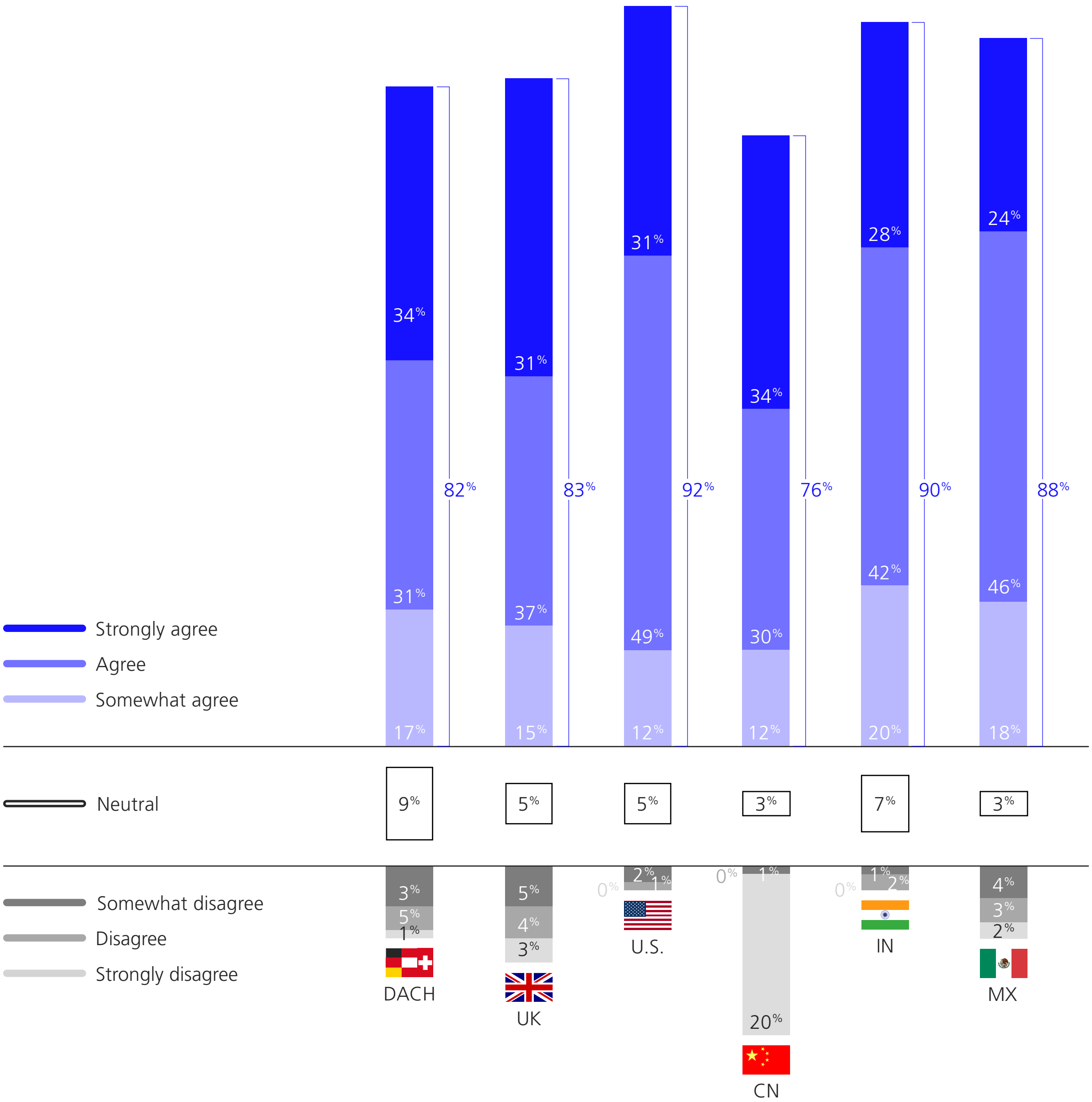


Fig. 17: Status of IT security by region / n – 1,206

The results make it clear that companies today do not view IT security merely as a technical necessity, but are embedding it as an integral part of corporate governance. At the same time, the development of authorization concepts shows that individual operational measures have not yet been implemented comprehensively and that further action is still required. The consequences of inadequate IT security are becoming more severe, as increased connectivity, cloud usage, and professionally operating cybercriminals pose risks not only of operational disruptions and financial losses, but also of reputational damage and significant regulatory penalties. This underscores the need for companies to adopt a more strategic approach to IT security.

The international comparison reinforces this trend. All regions exhibit a high level of maturity and are closely aligned in their self-assessments (Figure 17), for example regarding the use of a unified authorization concept for access to company data. The U.S. (92 percent) and India (90 percent) lead, followed by Mexico (88 percent), the UK (83 percent), and the DACH region (82 percent). China lags slightly behind at 76 percent.

The results show that the adoption of unified authorization systems is already well advanced worldwide. At the same time, the differences highlight that even in regions with high adoption, there is still potential for optimization.

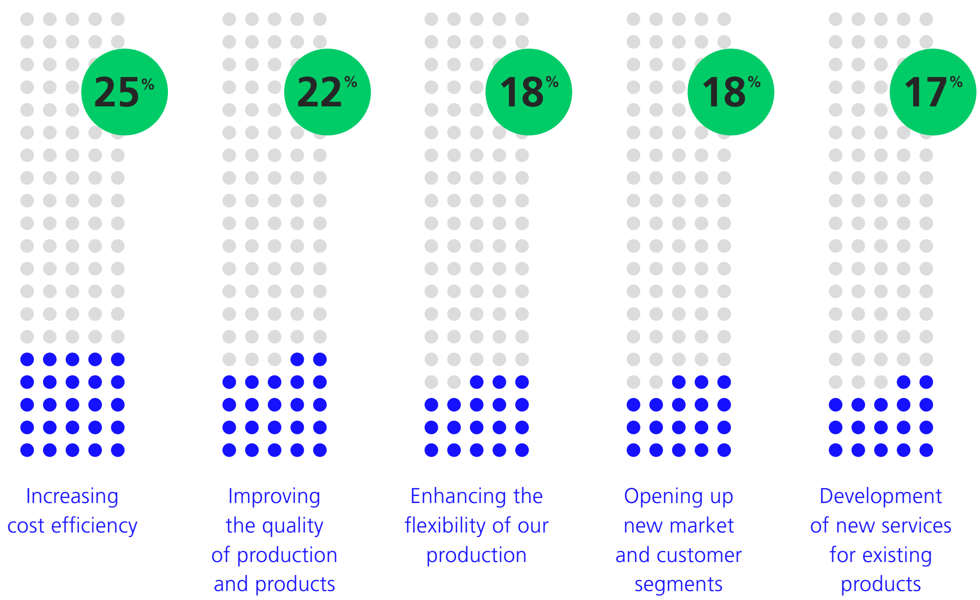
2.1.3 Topic Cluster 3 Strategy and Goals

Within the Strategy and Goals cluster, respondents were asked to distribute 100 points among five strategic corporate objectives of Industry 4.0. The results indicate that increasing profitability, as in the previous year, continues to be considered the most important objective, with an average of 25 points (Figure 18). Nevertheless, compared with last year, this represents a decrease of five points. This indicates that companies are increasingly moving beyond purely economic efficiency gains and placing greater emphasis on additional strategic dimensions.

The goal of improving the quality level of production and products remains in second place with an average of 22 points, and is thus still identified as a key driver for Industry 4.0. At the same time, the development of new market and customer segments, as well as the adjustment of production flexibility are gaining noticeably in importance, each with an average of 18 points. Both objectives show an increase compared with the previous year, highlighting the growing strategic relevance of growth and adaptation-related aspects. This indicates a shift: Industry 4.0 is no longer viewed solely as a tool for boosting efficiency, but increasingly as a lever for market expansion, individualized customer engagement, and agile adaptation to volatile demand conditions. Companies are therefore recognizing that digital technologies also open up opportunities for growth and differentiation.

With 17 points, the development of new services ranks lowest among the strategic objectives. As other goals gain in importance, this aspect falls further in the prioritization, even though the point value remains unchanged from the previous year. This shows that many companies recognize the potential of service-oriented business models, but their implementation is not yet a strategic focus – possibly because new competencies and organizational structures would be required.

Strategic Industry 4.0 focus
of the companies surveyed



Respondents could allocate a total of 100 points.
The results shown here represent the average score for each response option.

Fig. 18: Strategic Industry 4.0 focus of the surveyed companies / n – 1,206

The international comparison reveals significant differences in strategic focus. The DACH region places particularly strong emphasis on increasing profitability, with an average score of 30 points. This focus on efficiency and cost reduction reflects a traditionally more conservative, stability-oriented industrial philosophy. As a result, forward-looking goals such as entering new markets or developing innovative services take a back seat compared with the other regions. A similar, albeit somewhat more balanced pattern can be observed in the U.S. and the United Kingdom, where economic considerations also predominate but are more strongly combined with flexibility objectives.

A contrasting picture emerges in India: Here, the focus is on improving quality, with an average of 25 points, while profitability ranks second with 20 points. This indicates a strategic prioritization of production optimization – possibly in response to global competitive pressure and the need to meet international quality standards. In Mexico, cost efficiency and quality are given equal weight, each receiving 22 points.

Compared to all other regions, China exhibits the most balanced distribution pattern across all strategic objectives. Particularly noteworthy is that both the development of new services (18 points) and the expansion into new market and customer segments (20 points) are weighted more strongly here than in the other regions. This underscores China's strategic focus on innovation, diversification, and customer proximity – key pillars of industrial development within the framework of the national digital strategy.

30 points
Increasing **economic efficiency**

25 points
Improving the **quality** of production and products

22 points
Enhancing in **profitability** and for improving the **quality** of production and products

20 points
Opening up new market and customer segments

Overall, the results reveal a strategic shift: While traditional efficiency goals continue to form the core of Industry 4.0 strategies, aspects related to growth, flexibility, and innovation are noticeably gaining in importance. The DACH region in particular still shows some catching-up potential, as its industrial policy remains more focused on preservation and process optimization, whereas countries such as China and India are placing greater emphasis on dynamic growth, service innovation, and market expansion. These differences point to varying stages of development and risk tolerance in the implementation of digital-industrial strategies.

2.1.4 Topic Cluster 4 **Obstacles**

In the current survey, an increase in importance can be observed across all surveyed barriers compared with the previous year. The most significant obstacles are both the shortage of skilled workers and the challenge of integrating historically grown legacy IT systems. In 2025, only 41 percent of respondents report delays in adopting Industry 4.0 technologies due to difficulties in recruiting qualified employees. In 2026, this figure rises to 54 percent (Figure 19). This may be partly explained by increasing requirements for top talent and their qualifications, which are in high demand due to new technologies and rising innovation pressure. In addition, it should be emphasized that delays in the introduction of Industry 4.0 technologies due to historically grown legacy IT systems remain one of the most strongly perceived barriers, as this figure increases from 48 percent in the previous year to 52 percent in 2026.

Uncertainty regarding ROI rises even more markedly, from 38 percent of respondents in 2025 to 51 percent in the current survey. In the international comparison, ROI uncertainty stands out particularly in the U.S. and China compared to other obstacles. This perceived uncertainty may be attributed to increasingly unpredictable markets and new, unfamiliar technologies. Although the integration into day-to-day operations ranks lowest overall among the obstacles to technology adoption at 46 percent, closely followed by a lack of management attention at 49 percent, the DACH region in particular struggles with day-to-day operational burdens. This could be interpreted as a consequence of increasing bureaucracy. In 2025, supply chain issues were perceived as a barrier by only 31 percent of respondents. This value increases by almost 9 percentage points in 2026, which may be seen as a consequence of factors such as U.S. tariffs and China’s export controls, rising energy and raw material prices, or other geopolitical events.

While the obstacles are perceived to be the least significant in the U.S., Indian companies rate them the highest on average. Across all regions, difficulties in hiring qualified employees and challenges posed by historically established legacy IT systems are cited most frequently, with average values of 54 and 52 percent respectively. In Mexico, as many as 60 percent of respondents identify historically grown IT legacy systems as an obstacle to the adoption of Industry 4.0 technologies (Figure 20.2). It is also noteworthy that existing data silos are increasingly perceived as a barrier in all regions compared with the previous year, cited on average by 49 percent of respondents, including the newly added regions India and Mexico. The figures for these countries are particularly high at 68 and 55 percent respectively (Figure 20.1). The same applies to the perception that the adoption of Industry 4.0 technologies is delayed due to the lack of end-to-end data exchange with partners along the value chain. In the assessment of this barrier, only the UK records a decline, from 41 to 35 percent.

The implementation of Industry 4.0 technologies is delayed in our company due to …

54%

strongly agree 8%
agree 20%
somewhat agree 26%

… the shortage of skilled labor.

52%

strongly agree 7%
agree 21%
somewhat agree 24%

… established, legacy IT systems that have evolved over time make integration difficult.

51%

strongly agree 8%
agree 18%
somewhat agree 25%

... uncertain ROI.

49%

strongly agree 5%
agree 17%
somewhat agree 27%

... the supply chain issues lacking the necessary resources.

49%

strongly agree 8%
agree 19%
somewhat agree 22%

... a lack of consistent data exchange with partners along the value chain.

49%

strongly agree 8%
agree 18%
somewhat agree 23%

... insufficient capacity in day-to-day operations.

48%

strongly agree 6%
agree 19%
somewhat agree 23%

.... supply chain issues.

48%

strongly agree 7%
agree 17%
somewhat agree 24%

... lack of data exchange with partners.

46%

strongly agree 4%
agree 17%
somewhat agree 25%

... integration into day-to-day operations.

Fig. 19: Obstacles to the adoption of Industry 4.0 technologies / n – 1,206

The introduction of Industry 4.0 technologies is delayed in our company because data silos hinder the implementation of cross-functional solutions.

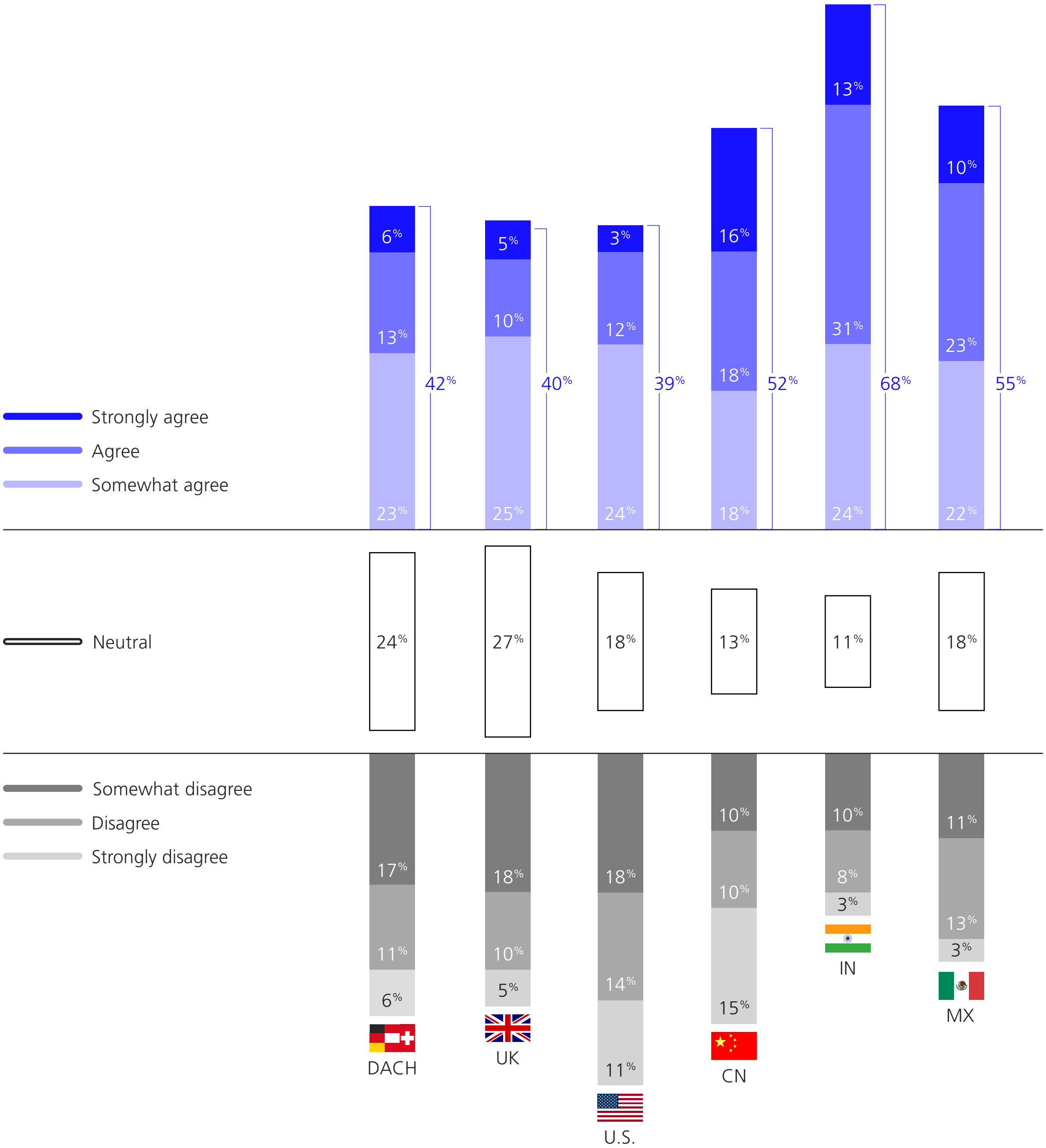


Fig. 20.1: Obstacles to the implementation of Industry 4.0 technologies by region – Data silos / n – 1,206

The introduction of Industry 4.0 technologies is delayed in our company because established, historically grown legacy IT systems make integration more difficult.

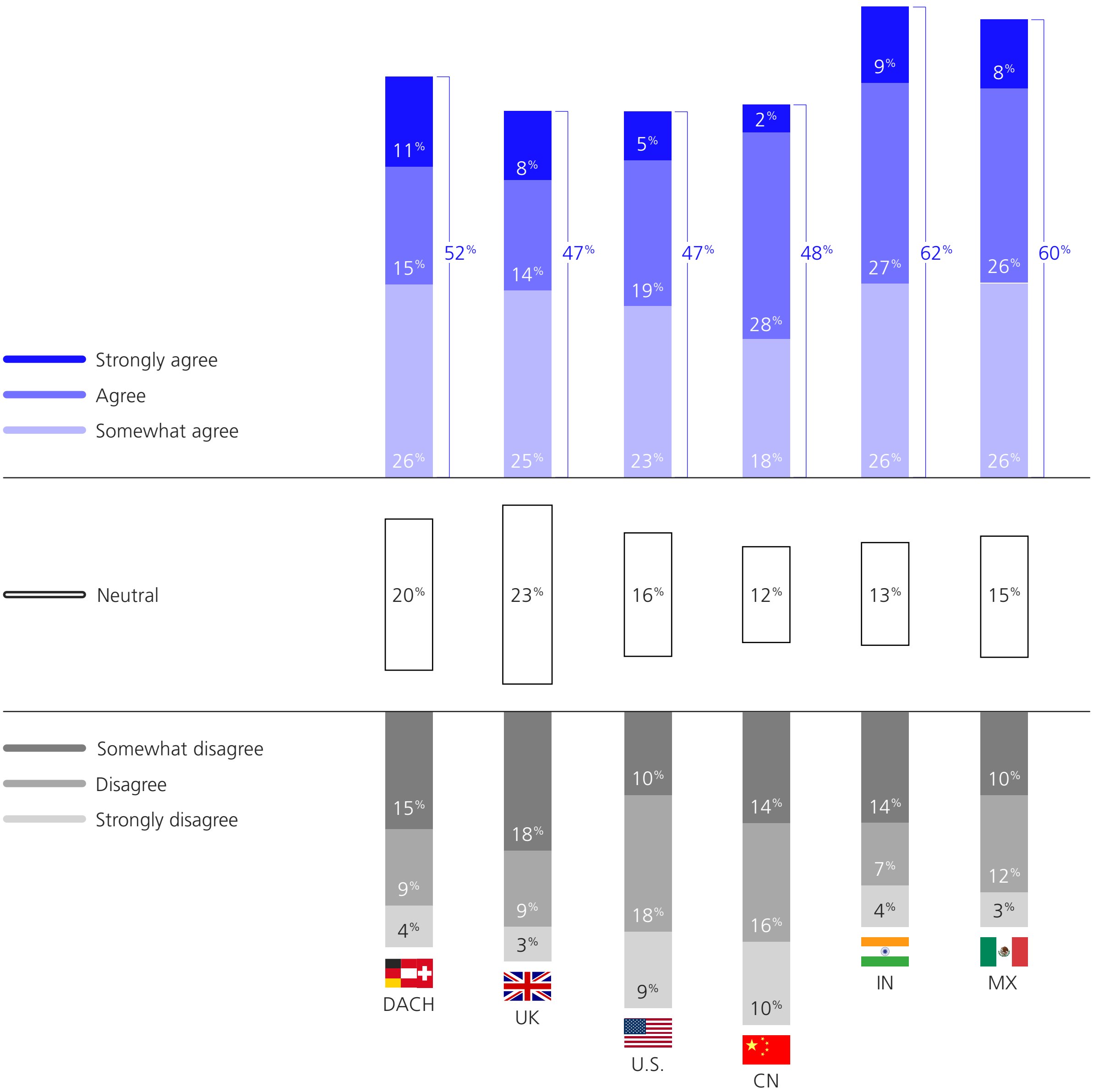


Fig. 20.2: Obstacles to the implementation of Industry 4.0 technologies by region – Legacy IT systems / n – 1,206

Industry 4.0 Barometer 2026

Software-Defined Manufacturing

UNLOCKING & ORCHESTRATING THE POTENTIAL OF EMERGING TECHNOLOGIES

This year's Industry 4.0 Barometer analyzes the current state of **SDM**, identifies key challenges and success factors, and provides guidance for companies seeking to actively shape the transition to Software-Defined Manufacturing.

2.2. Software-Defined Manufacturing: Prerequisites, adoption, key technologies, and success factors

Traditional, hardware-centric factories are facing profound changes. Analyses and surveys indicate that companies are increasingly turning to data-driven, software-controlled production approaches to enhance their adaptability and resilience.

In this context, **Software-Defined Manufacturing (SDM)** is a key transformation principle: It refers to the decoupling of physical production systems from their control logic through the consistent use of software. In place of rigid, hardware-dependent processes, an agile production IT architecture is emerging, in which machines, systems, and production processes can be orchestrated and optimized in real time using configurable, modular software.

Last year, the Industry 4.0 Barometer focused on the topic of data-driven production as the foundation for transparency, control, and value creation. This year, the focus is on the next step: How can data be used to make production processes intelligent, adaptive, and scalable? In this context, SDM provides the technological and methodological answers. These include digital twins, IIoT platforms, and cloud-based control. This can be supplemented by AI-powered optimization and software solutions capable of flexibly adapting machine behavior and process flows.

At the same time, new challenges are emerging: How can existing IT/OT infrastructures be integrated? What skills are needed? And how is the role of software in production management fundamentally changing?

This year's Industry 4.0 Barometer analyzes the current state of SDM, identifies key challenges and success factors, and provides guidance for companies seeking to actively shape the transition to Software-Defined Manufacturing.

At the same time, **new challenges** are emerging:

What skills are required?

How can existing IT/OT infrastructures be integrated?

And how is the role of software in production management fundamentally changing?

ElringKlinger

Success Story

ElringKlinger – On the path to a software-defined factory

Achieving flexible, scalable, and future-proof production with MHP

Initial situation and challenges

The automotive industry is undergoing a profound transformation. New drive technologies, a growing number of variants, shorter product life cycles and increasing cost pressure are forcing manufacturers and suppliers to rethink their production systems. For the global automotive supplier ElringKlinger, which, with sales of around €1.8 billion, is one of the leading system partners in the automotive industry worldwide, this means that manufacturing and intralogistics must become more agile, more efficient and more sustainable – without sacrificing quality or traceability.

To date paper-based processes and isolated data silos have made it difficult to achieve a comprehensive view of processes and data-driven production control. In addition, new projects have led to increased demands in terms of process optimization and the traceability of process data, serial numbers, and products.

Against this backdrop, ElringKlinger decided, in collaboration with MHP – A Porsche Company, to lay the foundation for an integrated production and logistics system architecture. The goal was to digitalize processes and create a scalable, highly flexible production environment – key building blocks on the path to a software-defined factory.

Software-Defined Manufacturing – the conceptual framework

By the term Software-Defined Manufacturing (SDM), MHP means an approach in which hardware and software are decoupled in production in order to make manufacturing processes flexible, efficient, and data-driven.

The SDM framework consists of five so-called building blocks: Communication, Data Insights, Standardized Models, Process Orchestration & Optimization, and IT/OT Operations. Not every company needs or fully implements all of these building blocks.

Rather, the key is to deploy the appropriate components in a modular fashion in order to increase the company's individual maturity level and to gradually achieve flexibility, transparency and agility in production.

In the collaboration with ElringKlinger, three of these five building blocks were used: Communication, Data Insights, and IT/OT Operations. This established the essential foundations for Software-Defined Manufacturing.

Approach and operational model

In close collaboration with MHP, ElringKlinger adopted a step-by-step approach that took into account both technological and organizational aspects. The implementation of the SAP Digital Manufacturing (SAP DM) and SAP Extended Warehouse Management (SAP EWM) solutions formed the operational foundation for this approach. These systems were not only implemented but also integrated in a way that supports the fundamental principles of Software-Defined Manufacturing.

Building Block 1: Communications

Standardized interfaces and secure communication

Based on an evaluated target shop floor architecture, defined communication methods, and relevant security considerations, the project team developed standardized specifications for all machines. Through standardized interfaces, such as OPC UA, machine data can be centrally collected, analyzed, and flexibly adjusted. As a result, production control is no longer tied to specific hardware.

Building Block 2: Data Insights

Data as the basis for decision-making

With the introduction of a digital shop floor, all relevant production data was collected centrally and made available for analysis. Workstations are equipped with state-of-the-art terminals that enable employees to record and visualize process data, order progress, and quality metrics in real time. Paper-based documentation has been completely eliminated. Via dashboards in SAP Digital Manufacturing, the synchronized inventory levels of the production supply areas can be viewed directly, without any system disruption – ensuring seamless integration between production and intralogistics.

Building Block 3: IT/OT Operations

Integration of IT and manufacturing systems

By integrating IT and OT systems, data from machinery, production lines and logistics can be processed within a unified system landscape. This enables a secure, scalable architecture that responds flexibly to new requirements and supports continuous process optimization. Machine data, reject rates and material flows are managed in an evidence-based manner – a crucial step towards greater stability and transparency on the shop floor.

Results and outlook

With the introduction of its fully integrated system landscape, ElringKlinger has taken a decisive step toward future-proof, flexible manufacturing. The new solutions allow processes to be adapted via software without requiring physical interventions on the production line. As a result, new process optimizations can be implemented more quickly, and production capacities can be used more efficiently.

By combining SAP DM and SAP EWM, the company has established a seamless flow of information between the shop floor and intralogistics. Material provision, production control, and order confirmation are now fully digitally integrated. ElringKlinger is benefiting from a significant reduction in manual work, greater transparency, and sustainable, paperless production.

Furthermore, the close collaboration with MHP provides the foundation for rolling out the concept to additional plants and production areas in the future.

Key facts & benefits

Efficiency & transparency
- Seamless flow of information between production and logistics
- Real-time data integration and centralized process control

Flexibility & scalability
- Software-based customization of production processes
- Rapid integration of new lines or sites

Sustainability & quality
- Fully paperless manufacturing
- Reduction of scrap and rework through data-driven process optimization

Success through partnership
- MHP as a strategic enabler for software-defined production
- ElringKlinger is establishing itself as a pioneer in modular, future-proof manufacturing systems

CONCLUSION

The joint initiative by ElringKlinger and MHP provides an impressive demonstration of how traditional manufacturing concepts can be transformed through an integrative system architecture. The decoupling of hardware and software, combined with intelligent data orchestration, provides the foundation for highly flexible, efficient and resilient production.

CONTACT

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2.2.1 Digitalization and software-driven approaches – current status

Against this backdrop, the survey reveals that the majority of companies expect significant disruptions brought about by digitalization and software-driven approaches over the next ten years. 31 percent firmly believe that their industry will undergo fundamental changes as a result, and a further 51 percent consider this at least likely. This suggests that these companies are already preparing for the upheaval and that there is awareness of it.

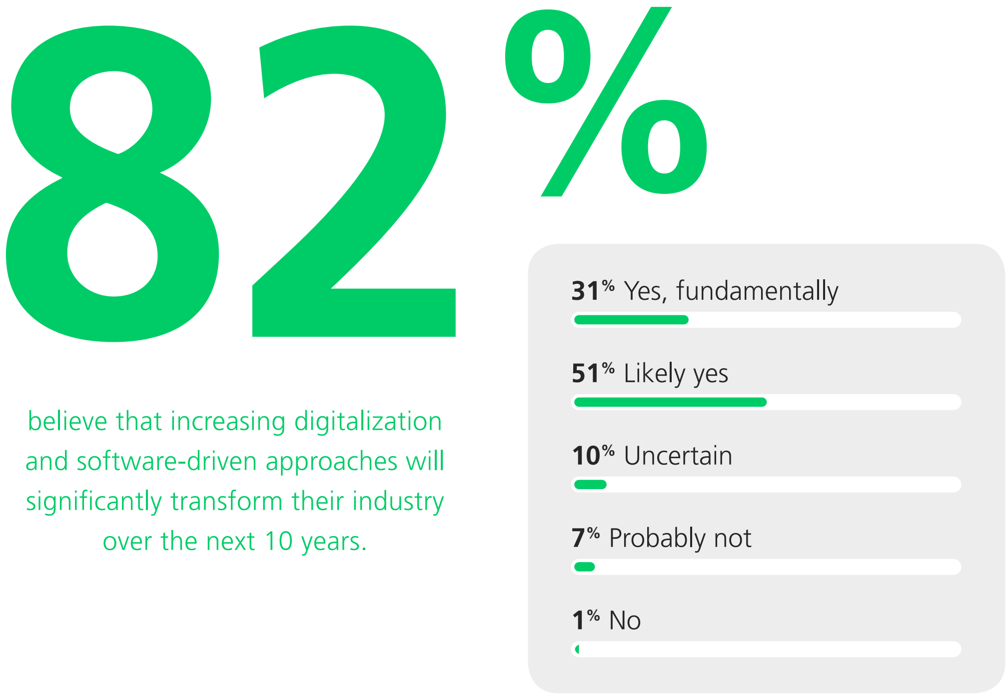


Fig. 21: Outlook for the industry / n – 1,206

However, a look at the international comparison reveals significant differences in perceptions. In India, 44 percent of respondents are firmly convinced that software-driven approaches will fundamentally transform their industry, whereas in the DACH region, the proportion is only 17 percent (Figure 22). This discrepancy shows that, when it comes to software-driven approaches, India has significantly higher expectations of change and, therefore, a more pronounced readiness for transformation. Companies in the DACH region view the disruptive potential of such developments as less significant and are more likely to wait and see how the transformation unfolds. Meanwhile, India is demonstrating a more pronounced software-first mindset and a faster adoption of digital technologies. The relevance of change often only becomes apparent when new market environments emerge or competitive conditions change, as is the case with V4Smart (see p. 78), which adopted software-based production approaches at an early stage. This becomes particularly evident when a company's own competitiveness comes under pressure as a result.

Do you believe that increasing digitalization and software-driven approaches will significantly transform your industry over the next 10 years?

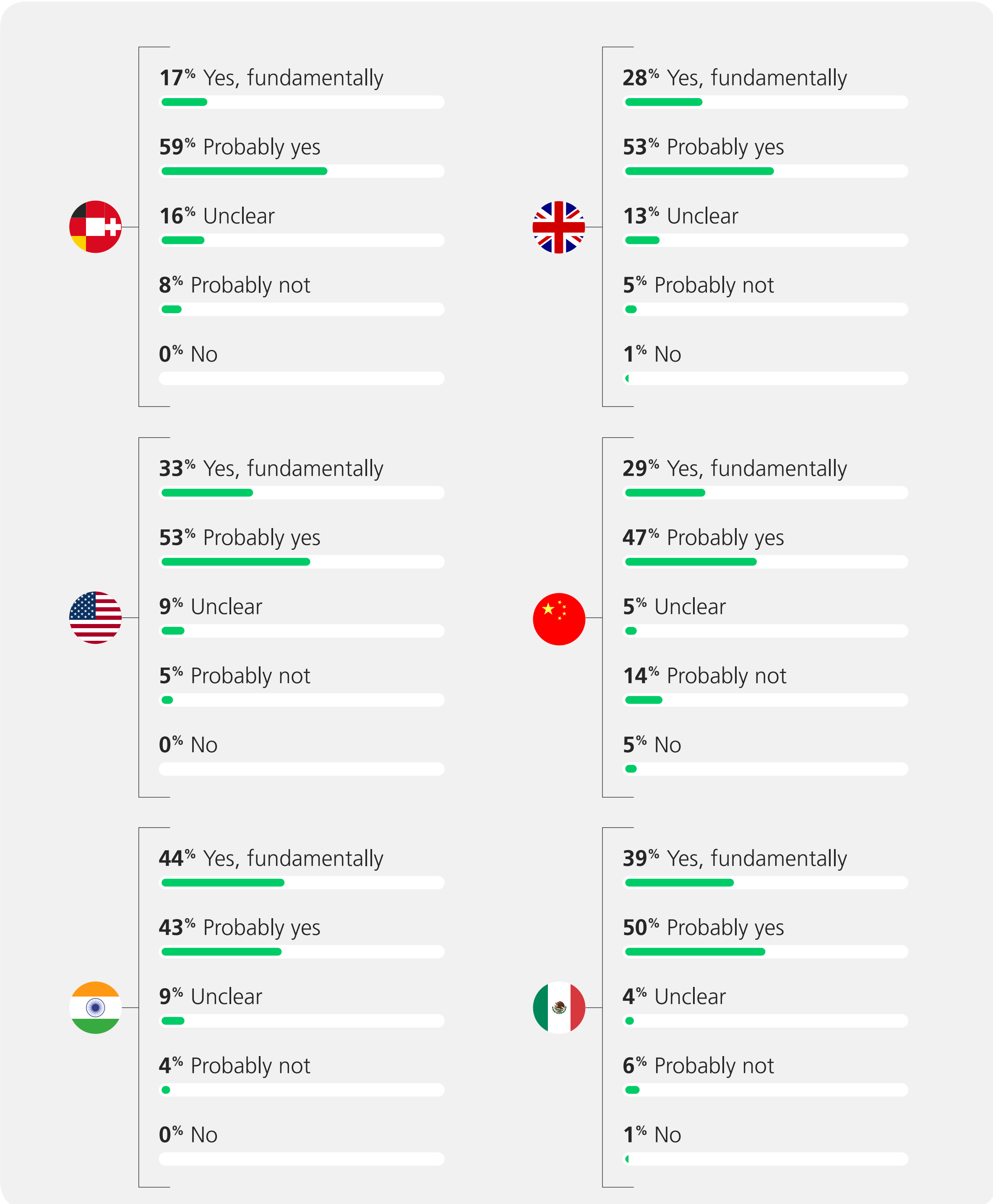


Fig. 22: Outlook for the industry by region / n – 1,206

2.2.2 Software-Defined Manufacturing – current status

The growing relevance of software-controlled approaches is also reflected in the survey on this year's focus topic, Software-Defined Manufacturing. The majority of respondents already have some familiarity with the concept. While only 12 percent of respondents have no exposure to the approach at all, 32 percent report that they are familiar with the concept but have not yet actively trialed or tested it. 39 percent of respondents are already conducting specific tests and technology assessments. Finally, 17 percent of respondents have already integrated the Software-Defined Manufacturing concept and report that they are very familiar with it (Figure 23). Internationally, this clearly shows that a large proportion of companies are exploring the concept or are even already in the implementation phase.

How familiar is your company with the concept, not the term, of Software-Defined Manufacturing?

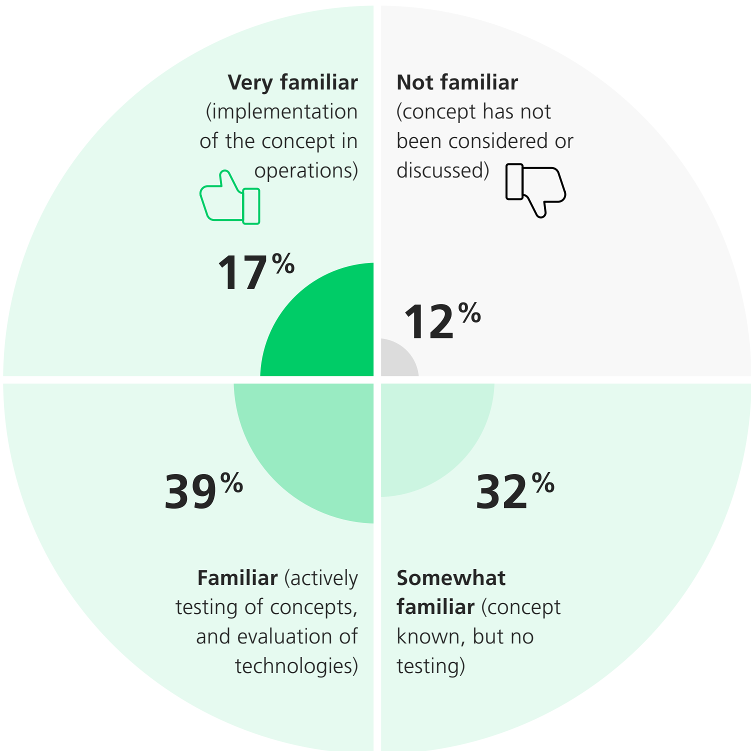


Fig. 23: Familiarity with Software-Defined Manufacturing / n – 1,206

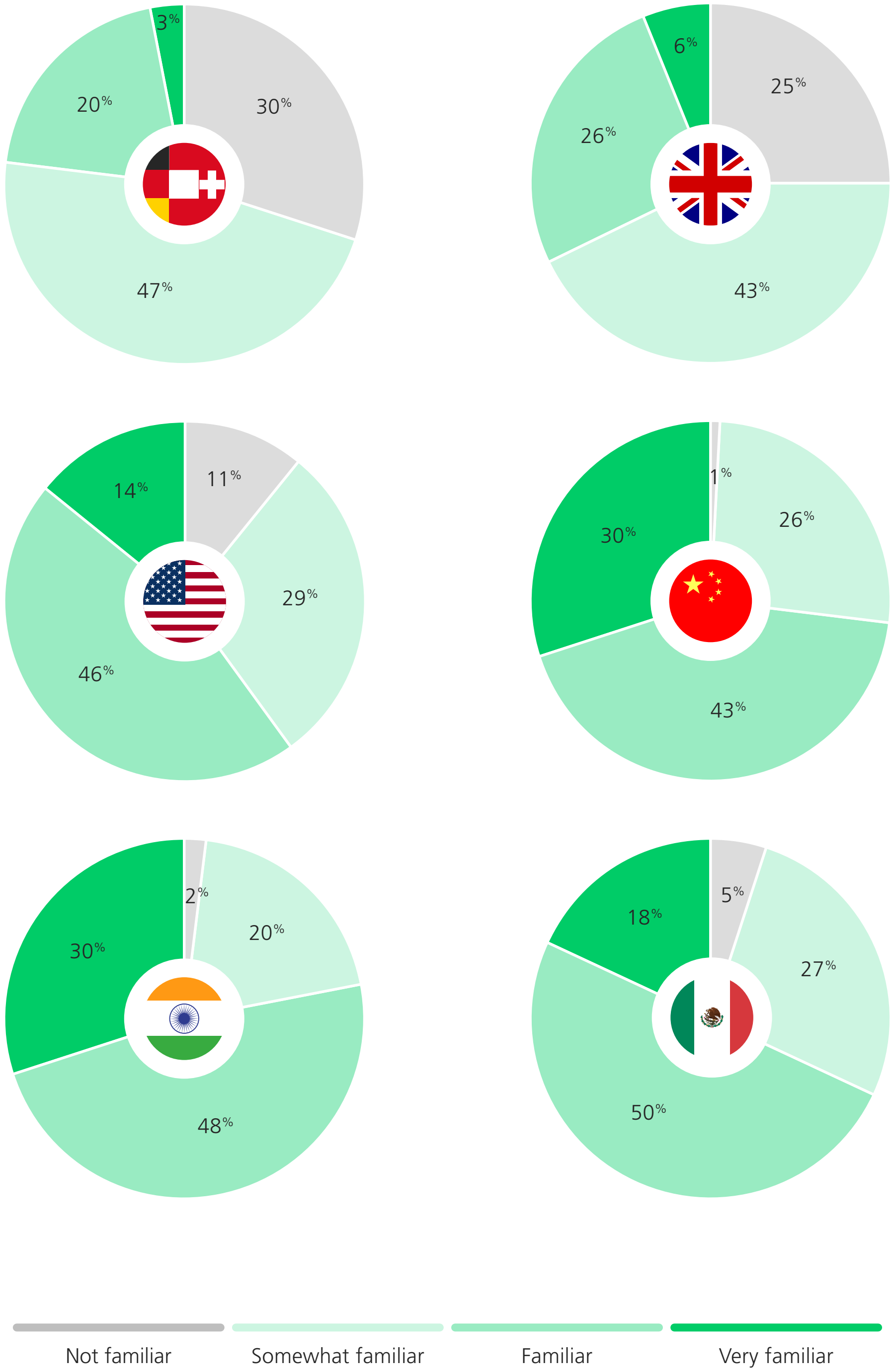


Fig. 24: Familiarity with Software-Defined Manufacturing by region / n – 1,206

The global comparisons of familiarity with the concept are particularly interesting. Here, too, India leads the way. Along with China, respondents in both countries report a very high level of familiarity, at 30 percent each. In the DACH region (3 percent) and the United Kingdom (6 percent), a significantly lower proportion of respondents report a high level of familiarity with the SDM concept. The U.S. (14 percent) and Mexico (18 percent) are in the mid-range (Figure 24). Similar to the expectations regarding software-driven approaches in the industry, the leading position of India and China can be explained by the fact that, in these countries, strong software expertise and government digitalization initiatives are likely driving the accelerated implementation of such approaches.

2.2.3 Manufacturing – status quo

To gain a deeper understanding of the status quo in industry, particularly in manufacturing, respondents were asked about their capabilities in the key dimensions of Software-Defined Manufacturing. The aim is to gain a sense of how far companies have already progressed on the path to a software-defined, data-driven production environment.

The focus is on **five core capabilities** of modern production systems that make up the SDM concept:
Flexibility: software-based adaptation of production processes
Self-optimization: continuous, data-driven improvement of operational processes
Scalability: rapid response to market demands without significant hardware changes
Connectivity: end-to-end networking of machines, sensors, and systems
Modularization: independent and flexibly combinable production modules

How would you assess the current status quo of your production operations in terms of …

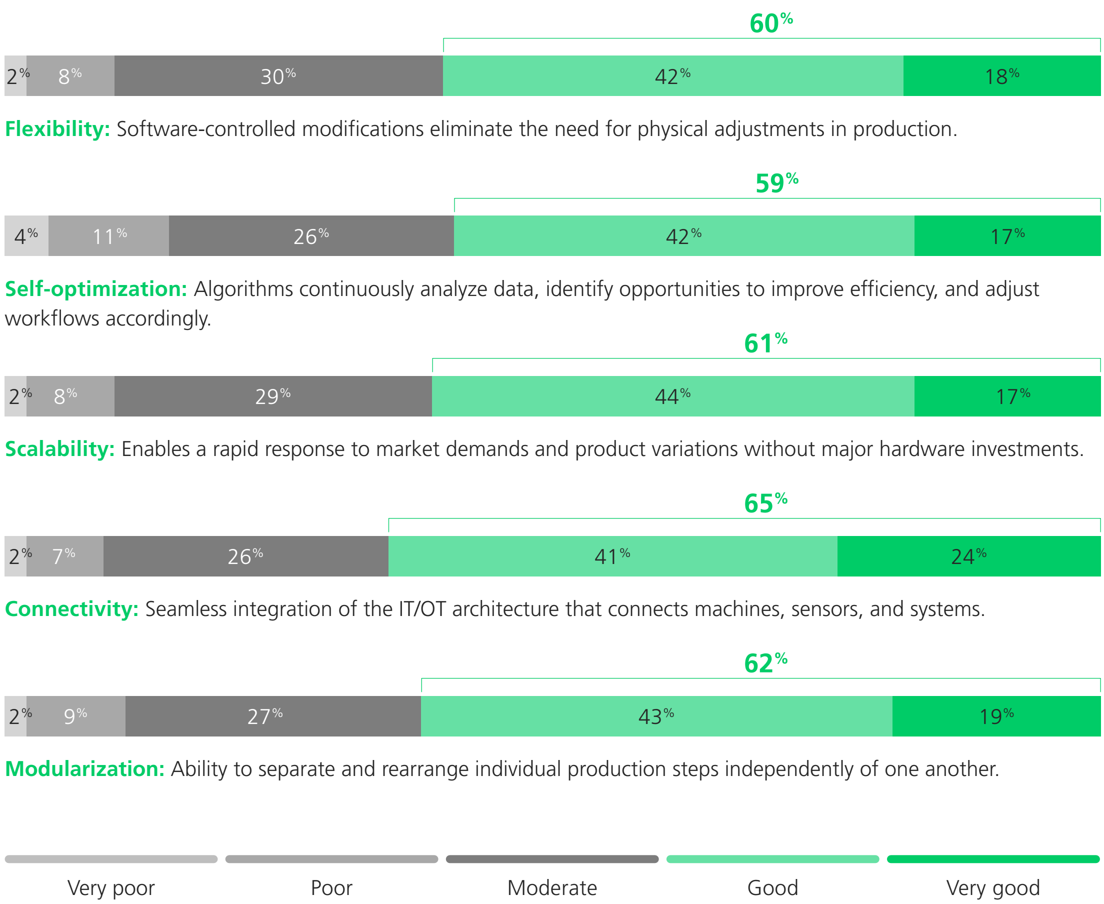


Fig. 25: Current state of production / n – 1,206

How would you assess the current status quo of your production in terms of flexibility, self-optimization, scalability, connectivity, and modularization?

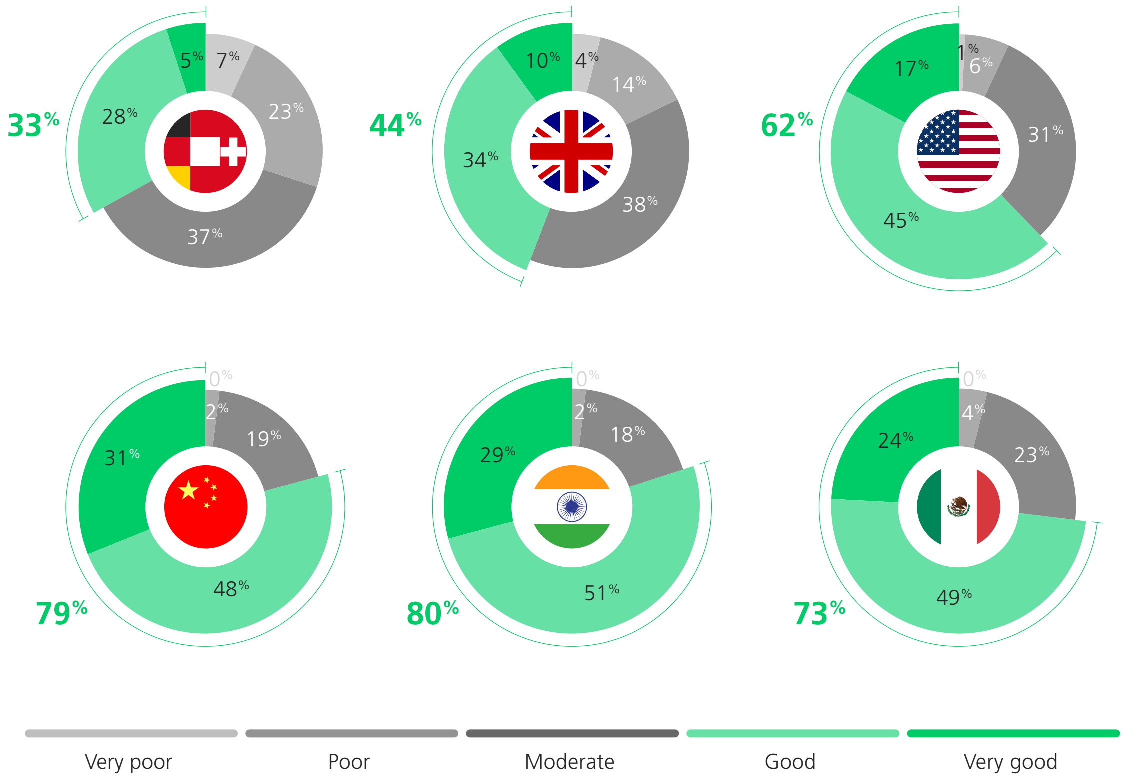


Fig. 26: Current state of production by region / n – 1,206

Overall, the results paint a surprisingly positive picture. A large majority of respondents, around 61 percent, rate the status of their production as good in the dimensions examined. A high level of maturity has already been achieved, particularly in the areas of connectivity and modularization. At 59 percent, the assessment of the capability for self-optimization is somewhat more cautious (Figure 25). There appears to be potential for systematic data analysis and for the use of real-time feedback to analyze and optimize work processes.

This positive picture becomes somewhat clouded when comparing countries. In particular, India with 80 percent, China with 79 percent, and Mexico with 73 percent rate their capabilities highly (Figure 26).

The differences in self-assessment across the globe can be explained primarily by differing industrial starting points and mindsets. While countries such as India, China, and Mexico view technological transformation as an opportunity for growth and have already established software-based approaches, a more hardware-oriented self-image continues to prevail in the DACH region. In addition, it can be assumed that a strong desire for perfection contributes to a more cautious assessment of one's own capabilities. Overall, a different mindset and a slower pace of implementation explain the DACH region's lag behind. There is still room for improvement, particularly when it comes to self-optimization of production. Furthermore, the low digital affinity of many machine manufacturers in the DACH region, both in terms of the digitalization of their products and their production processes, indicates that the transition to Software-Defined Manufacturing has so far been implemented only to a limited extent.

2.2.4 Adaptation of production processes

Building on the general assessments of the state of production, we now turn our attention to the optimization of production processes, which is considered the foundation of software-controlled production. Here, the results reveal a heterogeneous picture: Around 22 percent of respondents still primarily adapt their processes through manual reconfigurations. Another 28 percent have limited automation based on predefined options. Approximately 27 percent already use modular, software-controlled systems that allow for flexible adaptation. However, only just under a quarter of respondents report having reached the highest maturity level, where production processes are fully software-defined and dynamically controlled (Figure 27).

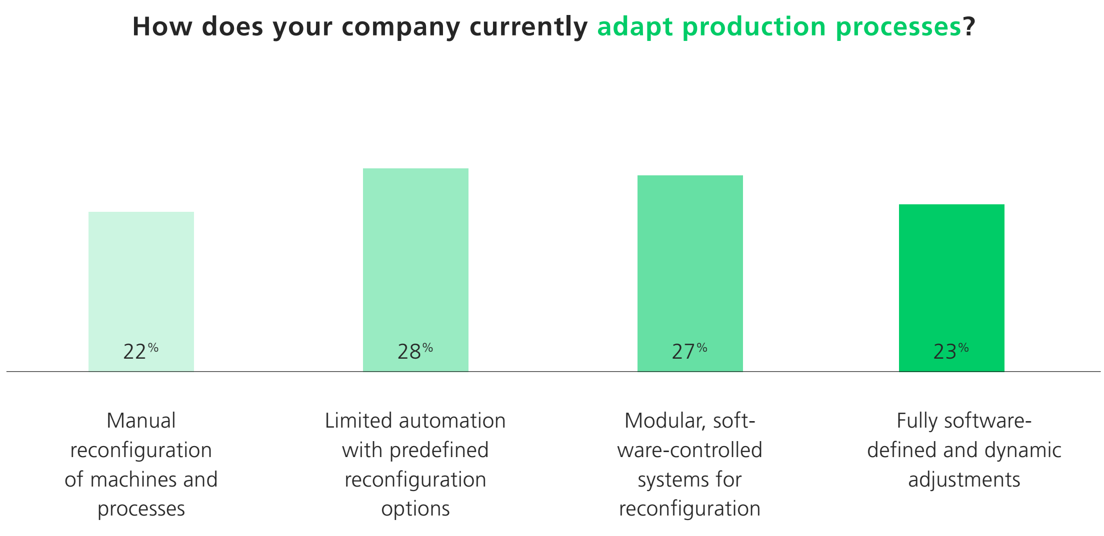


Fig. 27: Adaptation of production processes / n – 1,206

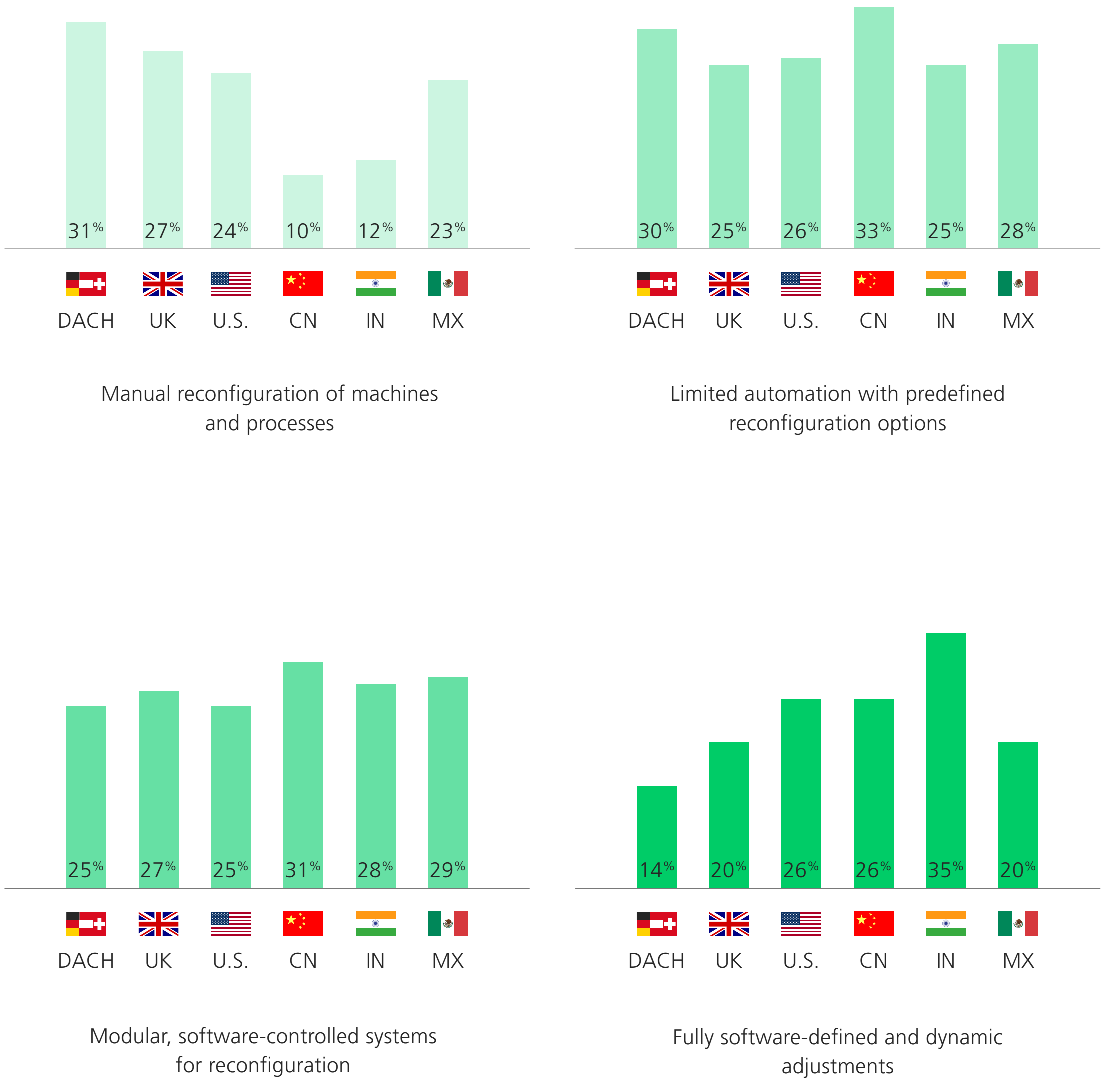


Fig. 28: Adaptation of production processes by region / n – 1,206

According to the survey, India leads in fully software-defined and dynamic adjustments at 35 percent, while the DACH region ranks last at 14 percent. China, the U.S., Mexico and the United Kingdom are in the midfield (Figure 28). It can be assumed that, in other regions, production processes are designed to be modular and software-controlled from the outset, whereas in the DACH region, digitalization is often implemented at a later stage. In the DACH region, the focus has traditionally been on mechanical precision, hardware, and traditional automation systems. Software is typically used as a supplement, which slows down the transformation to dynamic and self-optimizing processes.

2.2.5 Availability of real-time production data

The availability of real-time production data is a key prerequisite for software-defined production systems, as it provides the foundation for transparency, rapid decision-making, and automated process optimization. Overall, respondents demonstrate an advanced level of maturity in data utilization. At 97 percent, almost all companies already collect data in real time, indicating a well-established technical infrastructure. 58 percent of respondents actively use this data for decision-making. However, only 23 percent are already using real-time data for fully automated, AI-driven decision-making, which represents the highest level of maturity (Figure 29). Here, too, challenges lie in the diversity of system landscapes and in the technical implementation of end-to-end automated data usage.

In an international comparison, China stands out in particular. 89 percent of respondents report that data is already integrated but not yet analyzed in real time. Among them, 40 percent have already made significant progress: Their data is not only fully automated, but also enables AI-powered decision-making in real time. This places China in a leading position, well ahead of India (31 percent), Mexico (24 percent), the United States (23 percent), the United Kingdom (15 percent), and the DACH region (6 percent) in terms of the availability of real-time data in production (Figure 30).

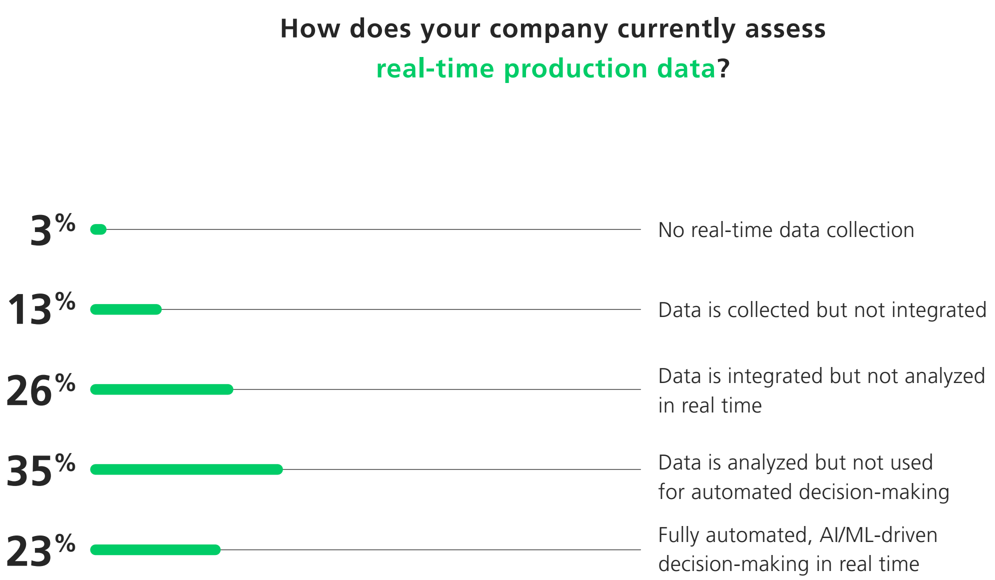


Fig. 29: Availability of real-time production data / n – 1,206

How does your company currently assess real-time production data?

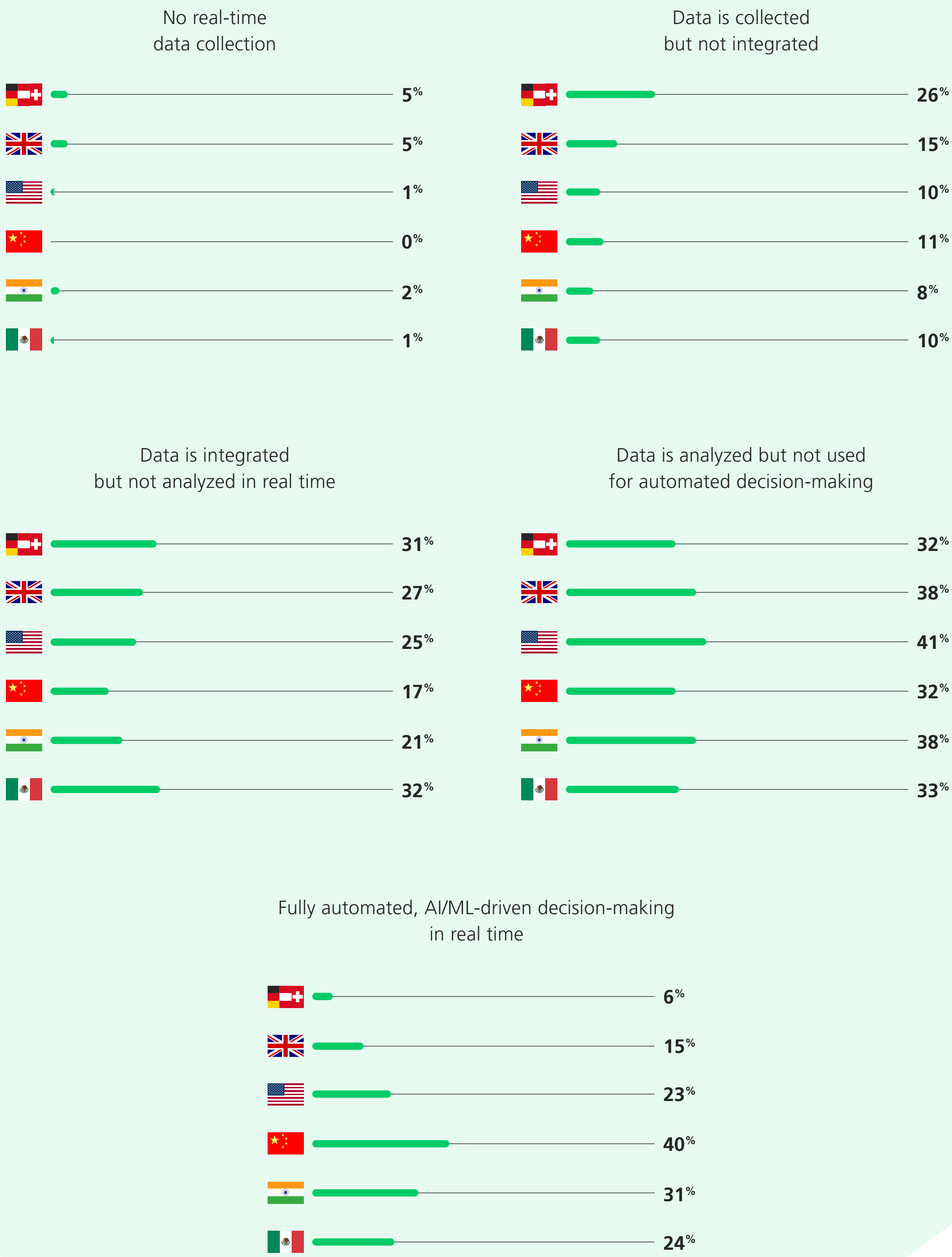


Fig. 30: Availability of real-time production data by region / n – 1,206

Software-Defined Manufacturing and real-world power: Insights into new battery production at V4Smart

Interview

Interview with V4Smart CEO Lutz Kramer. Interviewers: Henning Hiebsch and Niclas Maasackers

One of Europe's most advanced round-cell battery production facilities has recently opened in Nördlingen: **V4Smart**, the joint venture between Porsche and VARTA, aims to redefine battery cell production in Germany through software-controlled processes. In this interview, CEO Lutz Kramer explains how Software-Defined Manufacturing, a digital twin, and MHP made it possible to start series production within months.

V4SMART
German battery expertise since 1887

Henning Hiebsch (MHP):
Mr. Kramer, how would you describe V4Smart's current direction and strategic focus?

Lutz Kramer (V4Smart):
V4Smart was officially launched in March 2025 and, as part of a spin-off from the VARTA Group, took over a pilot plant. Our first task was to secure supplies for our customers – without interruptions, in sufficient quantities, and without compromising on quality. We succeeded in doing this, and this reliable, high-quality supply of battery cells remains our core business. Strategically, we are clearly focused on the development and production of high-performance lithium-ion round cells, with the highest power density and a very high energy density. Currently, we are the only manufacturer of lithium-ion round cells in Germany. Accordingly, in addition to technology, we also place great emphasis on resilient supply chains, as the battery industry is heavily impacted by geopolitical tensions and supply risks. In its current configuration, the new facility in Nördlingen produces up to 25 million cells per year. It is important to note that V4Smart was designed for scalability from the outset – in terms of both processes and overall conditions. We have designed the structures in such a way that we will be able to significantly increase production volumes in the future without causing fundamental system disruptions in the architecture.

Henning Hiebsch:
How would you assess the state of digital transformation in your production operations?

Lutz Kramer:
We took a two-pronged approach: Initially, we used an existing pilot plant in Ellwangen in a brownfield context to supply our customers. During this phase, we learned what it means to work without a fully mapped, end-to-end digital twin – in particular, the effort required to achieve traceability, i.e., the seamless tracking of various parameters. For our new plant in Nördlingen, we deliberately opted for a greenfield approach. Based on our experience with the brownfield site, it was clear that we absolutely needed a cloud-based solution that would enable a clean digital twin of the production process. Only in this way can we meet current and future efficiency requirements and overcome technological and quality-related challenges.

Niclas Maasackers (MHP):
You mentioned the digital twin. How was it implemented?

Lutz Kramer:
At the product level, the battery cell is fully digitally represented – with all its geometric features, its temperature and chemical behavior, and the associated simulation models. This is in line with the state of the art. We made the real breakthrough in the world of processes. We took a structured look at the manufacturing processes and defined which core technical parameters are critical from the cell's perspective and must be captured without fail. In addition, we systematically document the manufacturing parameters that determine a cell's properties. All of this feeds into our digital twin, which acts as a cloud-based representation of the factory: Machine states, setting and limit values, as well as the resulting quality data, are transferred to the digital world, analyzed there, and continuously fed back into physical production.

Niclas Maasackers:
How does the digital twin approach affect the start of series production and quality assurance?

Lutz Kramer:
The digital twin is central to a rapid ramp-up, high manufacturing quality, and on-time delivery. We detect issues in production much earlier than would be physically possible – ideally even before a cell is identified in the final test or arrives at the customer. The fundamental requirement is to design processes in such a way that no defective cell leaves our production facility, both physically and digitally. In this context, we refer to "digital rejects": During production, we record around 2,500 data points per cell, at a rate of approximately 80 cells per minute. A cell can be physically perfectly fine, delivering and receiving power – but it still needs to be rejected if its traceability is not complete, for example, if a critical parameter is missing or a limit value is not properly documented. This way of thinking – treating the physical and digital worlds as equally important – is a hallmark of our quality standard.

Henning Hiebsch:
A prominent application context is Porsche's sports cars. What requirements does Porsche AG have for the cells?

Lutz Kramer:
Porsche provided us with clearly defined requirements very early on, particularly regarding power and energy density. We jointly specified these requirements about three years ago, and they have now been fully implemented in production. When it comes to the 911 GTS and the Turbo S models, we can proudly say that this package was only possible thanks to the performance parameters of our cell.

We can precisely meet criteria such as charging and discharging rates, temperature behavior, size, and energy density. In addition, we ensure the most uniform quality distribution possible. We already consider our cells to be at the cutting edge of technology, and we are committed to further expanding this lead. This is also to prove that high technology can still be developed in Germany.

Henning Hiebsch:
What major hurdles have you encountered in digitalizing production?

Lutz Kramer:
Introducing an end-to-end digital twin is a complex change process involving many stakeholders: visionaries, architects, strategists, implementers – and, ultimately, the users of the system on the production floor. Everyone needs to understand the philosophy. We have handed over a key role as drivers to the MHPs, who have supported us with their extensive experience in establishing the structures and creating the digital representation. One of the major challenges was the data strategy: What data do we collect, with what priority and in what structure, to ensure that the physical world is clearly and fully translated into the digital world? This is not a one-way street; physical processes also need to adapt in order for the digital twin to function properly. We have thousands of copies of the cell in its physical form. The QR code printed on it serves as the label for the digital world, where traceability is mapped – a process that is essential for being able to declare the cell OK, with all its parameters.

Often, people only think about the digital dimension: bits and bytes, interfaces and data streams. However, what is often overlooked is the crucial role of training employees and developing the right mindset.

Henning Hiebsch:
Can you describe for us the new mindset that is needed and the roles of your employees in manufacturing?

Lutz Kramer:
In the beginning, it was telling that, when it came to questions about digitalization, everyone reflexively turned to IT – along the lines of, "This is an IT project, so you guys handle it." Of course, IT is a key enabler, but this approach only works if digital competence is widely established throughout the company. Even the best machine operator will reach their limits if they do not understand the digital aspects of their work. They need to know that every physical action – such as readjusting a machine – has a digital impact that needs to be tracked and updated in the system. Therefore, digitalization is not only transforming processes and systems, but also training, mindsets, and the way we collaborate. Only when the digital context becomes part of our day-to-day operations can we meet our efficiency and quality standards.

Henning Hiebsch:
How did you manage to bring the manufacturing experts and the digital specialists together around a shared understanding?

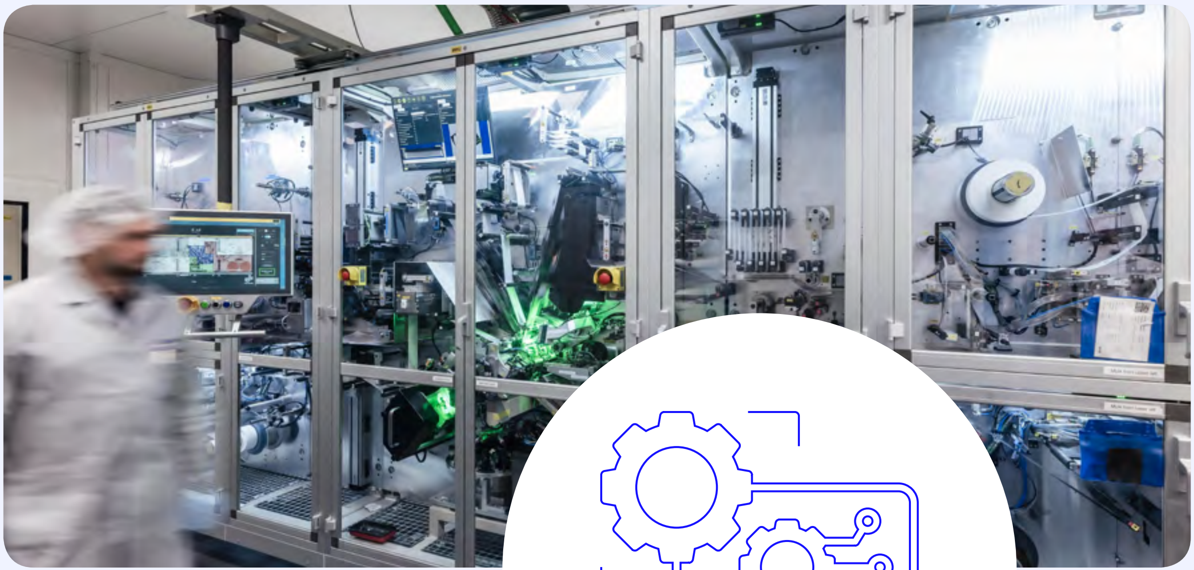
Lutz Kramer:
In the beginning, we had meetings where both sides spoke with great expertise, but they talked at cross purposes. A classic example was the term "master data": The manufacturing team had already explained procedures and processes multiple times, but they did not understand what was specifically expected. For the digital experts, on the other hand, it was perfectly clear what data they needed and how it had to be structured; for the physical side, however, this was not tangible.

Therefore, we opted for a two-way learning process. Our colleagues from the digital world came along to the production floor and familiarized themselves with machine processes, quality tests, and the actual information available to the workers. Conversely, we introduced the production team to basic data models, system logic, and prioritization. This mutual familiarization is not a one-off initiative, but an ongoing process – and, in my view, critical to success in a transformation project of this nature.

Henning Hiebsch:
You use the Software-Defined Manufacturing concept. What does V4Smart mean by this, and how do you assess its potential?

Lutz Kramer:
For today's mass production, with its demands for efficiency, speed, flexibility, traceability, and quality, I see no alternative to Software-Defined Manufacturing. For us, this means that physical manufacturing has a complete mirror image in the digital world – with all relevant parameters and states. The major advantage is that, in the digital realm, we can use tools that would be difficult or even impractical to employ in the physical world: trend detection, real-time monitoring, and predictive adjustment of process parameters. My ideal scenario is to be able to detect, starting from batch size 1, when parameters are trending in a critical direction and to take countermeasures almost in real time. Therefore, Software-Defined Manufacturing is not just a technical concept but a key driver of competitiveness.

Niclas Maasackers:
When you talk to decision-makers in the automotive industry, what developments do you see over the next few years?



"What sets us apart is our approach of making the digital twin the backbone of the factory without compromise. This is a key differentiating factor."

Lutz Kramer
V4Smart

Lutz Kramer:
Many companies are currently moving in the same direction: They want to set up their production operations in such a way as to create the most complete possible digital representation of the production structure – including machines, plant parameters, and product data. Only on this basis can modern AI methods be used effectively. The integration of AI is still in its early stages. We see enormous potential, particularly in the areas of trend identification, anomaly detection, and predictive control. However, without a consistently structured digital twin, AI will fall short of its potential.

Henning Hiebsch:
Where do you see V4Smart in 2030?

Lutz Kramer:
We operate in an environment where, to date, there are only a few comparable players in Germany and Europe. With our new, thoroughly digitally designed production line, we operate the most advanced European manufacturing facility for lithium-ion round cells. In particular, our approach of making the digital twin the uncompromising backbone of the factory is a key differentiating factor. We aim to establish V4Smart as a center of excellence for the development, production technology, and application of battery cells – with a clear focus on Germany and Europe as industrial hubs. This includes further developing our digitalized, Software-Defined Manufacturing, industrializing new generations of cells, and further strengthening our collaboration with technology and manufacturing partners. Our aim is to demonstrate that highly innovative battery cell production is not only possible in other regions of the world, but can also be implemented at the highest level in Europe, and in Germany in particular.

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2.2.6 Availability of production systems

A key advantage of Software-Defined Manufacturing is improved system availability, driven by rapid adjustments and scheduled machine maintenance. When asked how scheduled maintenance windows for updates or machine controls affect the availability of production systems, the results reveal a nuanced picture: 67 percent of respondents report minor to moderate impacts, while a further 26 percent experience significant or even severe disruptions. 7 percent stated that maintenance has no impact (Figure 31). This suggests that, in many companies, production systems are still heavily dependent on rigid maintenance cycles, and that flexible, software-defined systems have so far been adopted only to a limited extent. A key reason for this could be the high cost of traditional PLC programming, as well as the traditional goal of designing production environments for reliability and stability. However, this approach is increasingly at odds with today's demands for flexibility and rapid adaptability.

To what extent do scheduled maintenance windows for updates or maintenance of machine controls affect the availability of your production systems?

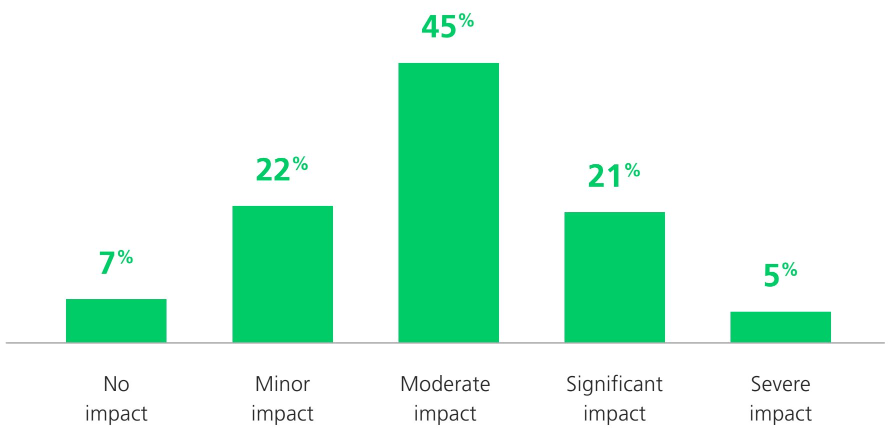


Fig. 31: Availability of production systems / n – 1,206

Especially when making capital investments in high-growth markets such as defense or battery production, Software-Defined Manufacturing should be considered from the outset to enable rapid industrialization, flexible scaling, and long-term competitiveness.

Dr. Walter Heibey
Partner
Porsche Group | Production
MHP

Courage pays off: From the cloud to the dynamic shop floor with Software-Defined Manufacturing

Interview

Interview with Chris-Markus Kratz, Global Director, Automotive & Manufacturing at Amazon Web Services. Interviewers: Prof. Dr. Christina Reich and Niclas Maasackers

With over 200 digital services in data centers located around the world, **Amazon Web Services (AWS)** is the most widely used cloud platform globally. Millions of B2B customers – from fast-growing startups to large corporations – use AWS to increase agility, reduce costs, and drive innovation. Manufacturing companies, in particular, can benefit from this. However, there are often obstacles and concerns when it comes to cloud and AI systems. In this interview, Chris-Markus Kratz explains how a successful transformation toward Software-Defined Manufacturing can still be initiated despite these challenges. In an interview, Chris-Markus Kratz explains how to successfully initiate the transition to Software-Defined Manufacturing. As Global Director of Automotive & Manufacturing at AWS, he understands the needs of automakers and manufacturing companies, and outlines his approach to brownfield structures and cultural barriers.

Niclas Maasackers (MHP):
You helped develop the manufacturing focus area for AWS. What does your area of responsibility entail – and how did you get involved in this topic?

Chris-Markus Kratz (AWS):
I am responsible for global business with a number of key accounts in my division, including Bosch, BMW, the Volkswagen Group, and also ABB, as well as suppliers such as Forvia and HERE. My team includes everyone who "has direct contact with the customer"; for example, in the context of Volkswagen, that means 300 to 400 people across all technical departments. A quick look back: In 2016, I moved from IBM to Amazon. At that time, Amazon Web Services was developing purely IT services, and we were in the process of figuring out how to approach the manufacturing industry. So my task was to analyze the needs and requirements of our potential customers.

I started, Amazon-style, with a blank sheet of paper and asked all C-level executives in the manufacturing industry in Germany what kind of collaboration they could envision. Two key aspects stood out in particular: First, the cloud was not yet a relevant topic in the manufacturing environment at that time. Second, there were significant differences in the technical framework, particularly in the interaction between IT and OT. Although both domains sometimes use identical terms, their meanings and technological implications differ significantly. This was valuable information for us at AWS in order to understand what the industry really needed. When we digitally transform a manufacturing operation, it's like open-heart surgery: There can be no downtime, or at the very least, it is very costly.

Niclas Maasackers:
What is your strategic focus?

Chris-Markus Kratz:
My focus is on major partnerships with the automotive and manufacturing industries. By partnerships, I don't just mean our services, which our customers use every day anyway – without our team. It's about the technologies and enablers that are needed for transformation. Amazon and AWS themselves have extensive manufacturing experience. For example, in manufacturing their own processors for cloud data centers and satellites for global broadband internet. These highly complex products are not created using off-the-shelf software, but rather based on specially developed microservices. That's precisely why we have a particularly good understanding of the challenges and needs of manufacturing companies.

Niclas Maasackers:
Particularly in the DACH region, many companies have grown organically over time and therefore operate within brownfield structures. In your opinion, what are the biggest obstacles and hurdles preventing these companies from benefiting from Industry 4.0 and digitalization?

Chris-Markus Kratz:
The barriers lie in the skills within the companies and in the culture, as well as in the organizational structures. At the Hannover Messe, I once asked the question: What is your biggest challenge? The managers said: a) energy costs in Germany and b) the difficulties associated with transformation. The key bottleneck is not in manufacturing expertise, but in digital capabilities. On the production line, companies naturally know what they are doing. However, there is often a lack of knowledge about how to transform a traditional production line into a highly automated and digitalized production system.

Prof. Dr. Christina Reich (MHP):
Are there too few people with specific digital skills?

Chris-Markus Kratz:
I think that, often, there is simply a lack of time and willingness to engage intensively with these topics and to develop the necessary understanding. In Germany, in particular, there is a clear resource problem. Talented individuals with an affinity for digital technology rarely choose traditional manufacturing jobs. Even if they do, companies often fail to retain them in the long term. This is exactly where AWS comes in.

Our solutions are designed to be as easy to use as possible. After all, when companies have to piece together customized solutions from numerous building blocks, this requires in-depth, specialized expertise. That's why, in addition to flexible modules, we also offer preconfigured package solutions that are ready to use out of the box. Both approaches are valid.

Niclas Maasackers:
How do innovations come about at AWS?

Chris-Markus Kratz:
We don't start with the solution; instead, we ask, "What problem do you actually want to solve as a customer?" We focus purely on the business side: for example, reducing scrap, avoiding selection risks, or preventing micro-downtimes. These problems are usually not technical in nature; rather, they relate to organizational issues and IT systems. One tool at Amazon is called Press Release Frequently Asked Questions (PR/FAQ): 95 percent of Amazon Web Services were created using this tool. We simply ask: "What problem would you like to solve, dear customer?"

Example: The idea behind the Kindle e-book reader was not to sell more books. Rather, it was based on customers' need to be able to read not just one book, but multiple books, while on vacation or at the beach. Thinking backwards: We are building a device on which books can be stored.

We also apply this customer-centric approach to the manufacturing industry: We develop practical services based on the analysis of specific customer experiences. At the same time, we identify recurring patterns, for example in the integration of production lines, and use these as a basis to build entire ecosystems.

Niclas Maasackers:
When innovations are developed on a small scale and, ideally, scaled up across a production campus and then globally across multiple production sites, IT and OT operational technologies need to work in close collaboration. How does AWS approach these two worlds?

Chris-Markus Kratz:
The biggest area of transformation in the automotive and manufacturing industries will be the shop floor. What hasn't worked in recent years is now becoming possible thanks to AI. Tools that currently automate software development will also be able to do so for OT in the future. Then, we will no longer have to deal with protocols and nomenclatures; an AI system will take care of that – smarter and more scalable than a human could ever be. The other key will be small language models or large language models on the edge, which will enable self-connecting production lines. You no longer have to connect each PNC and individual MES systems; agents will take care of that. We will now overcome this hurdle together with our partners and customers.

Unfortunately, those who don't use AI or transform their shop floor will be left behind. This means I have to empower brownfield companies to digitalize as quickly as possible – in a software-defined way.

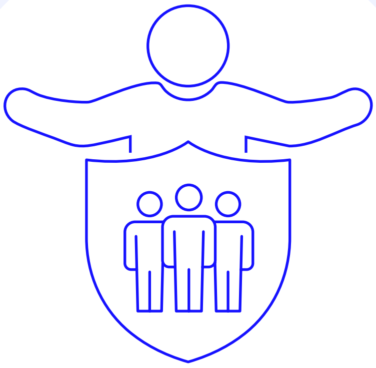
Niclas Maasackers:
What is your assessment of China? There, companies are faster at developing and using AI.

Chris-Markus Kratz:
In China, the question of AI no longer even arises; the only question is: How quickly can I implement agentic AI systems? In the U.S., companies often make top-down decisions: We're going in this direction; we're using AI in production; there are clear guidelines; and then it gets implemented – often in typical American fashion: "Let's discuss the problem when we have it." In Germany, we are still concerned about data protection and worried that knowledge will be extracted from the cloud. My wake-up call for Germany would be: We have collected an incredible amount of manufacturing data over the years, more than any other country. This is a global competitive advantage that we should finally leverage.

Niclas Maasackers:
But how can we alleviate people's fears? How do you win people over on this issue?

Chris-Markus Kratz:
For me, the production manager plays a central role in shop floor projects. A line manager is judged on output – if they see the benefits of the cloud, we're in the game. In Germany, on the one hand, we have a cultural issue within companies, and on the other hand, we have external restrictions.

A lot of things don't seem possible because of data protection, which is why we're where we are. This reminds me of the time when the cloud was being debated; you can apply that debate exactly the same way to GenAI. Only when the first movers build a competitive advantage do everyone else want to follow suit.



I'VE GOT YOUR BACK

There needs to be top-down guidance, meaning managers who say:

"We're going to do it this way now, and I'll have your back, even if things go wrong."

Chris-Markus Kratz
Global Director Automotive & Manufacturing
Amazon Web Services

Dr. Christina Reich:
If you no longer want to connect machines rigidly and locally via their respective permanently installed control systems, but instead want to be more flexible, control them in real time, and roll out scalable solutions, you quickly arrive at the topic of Software-Defined Manufacturing. Can you assess the potential of Software-Defined Manufacturing?

Chris-Markus Kratz:
Currently, in Germany, we are in the single-digit percentage range when it comes to Software-Defined Manufacturing – there is still a lot of room for improvement. I see the advantage as being that we can move away from these rigid lines. Self-connecting and self-optimizing lines make it easy when I need to adapt a production line or integrate a new machine. At the protocol and software level, this is already working today; for example, I can build an agent, a crawler, that understands the syntax and establishes connectivity.

In production, it's usually not major errors or malfunctions that cause problems, because those are identified quite quickly. It's the micro downtimes that add up. With artificial intelligence, we can address these issues much more quickly. One of the biggest benefits extends across the entire supply chain: No matter what downtimes or error patterns I see on the line, I can proactively control and align the entire supply chain – companies become significantly more efficient when they can see the end-to-end process and make adjustments.

Dr. Christina Reich:
For the vast majority of manufacturing companies, Software-Defined Manufacturing is still a vision for the future. How do we address the concerns before taking the first step?

Chris-Markus Kratz:
The path forward involves lighthouse projects. To do that, you have to find people within the company who are willing to take a risk. Amazon CEO Andy Jassy once shared a top-10 list of conditions for cultural and digital transformation. One crucial point on that list is that there needs to be top-down guidance, i.e., managers who say: "This is how we're going to do it now, and I'll have your back, even if things go wrong." Take Premium OEM as an example: In 2020, the manufacturer decided to become a data-driven company and, in my opinion, implemented this decision consistently.

This was a top-down decision made by the CFO, which led, for example, to the creation of a data lake. The departments that worked with it and shared their data became more efficient and faster than all the others. These experiences then generated the necessary positive ripple effect within the group – and other companies can also learn from this.

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2.2.7 Key technologies and success factors

The analysis shows very clearly that the companies surveyed are now able to clearly identify and prioritize the technological core of digital transformation. The percentages indicate how often a particular characteristic was selected as one of the top 3 most important factors. Three key elements take center stage: First, the seamless integration of IT and OT systems is rated as the most important technological lever, with 54 percent of respondents selecting it as a top-3 factor. Second comes the ability to collect and analyze data in real time and to feed it directly into operational decisions, which 51 percent of the companies surveyed include among the most important characteristics. Third, 46 percent consider self-directed and adaptive production capabilities to be among the key future characteristics of a modern production system (Figure 32). This order makes it clear:

Integration, real-time capability, and operational intelligence form the foundation of future-proof industrial value creation.

The crucial importance of IT/OT integration shows that companies are moving beyond the mere networking of individual systems and are instead striving for a holistic production architecture. The traditional separation between office IT and shop floor IT is increasingly seen as a historically outdated model. In practice, it leads to media discontinuity, redundant data storage, and a lack of transparency regarding critical processes. Therefore, companies view an end-to-end, interoperable data landscape not only as a technical goal but also as a structural overhaul of their value creation architecture. Therefore, IT/OT integration is less of a project than a systemic paradigm shift: from the piecemeal digitalization of individual machines to a networked, consistent production ecosystem. Therefore, IT/OT integration strategically forms the foundation, as without it, neither real-time capability nor adaptive control can be reliably achieved.

Respondents view the ability to capture and process data directly at the point where it is generated and to make it usable for operational decisions as a new fundamental principle of industrial control. It marks a shift away from retrospective, lagged reporting processes toward forward-looking, situational production management. In this context, real-time capability is not merely a technological feature but an organizational principle: It shortens decision-making paths, enhances process stability, and can make disruptions visible before they cause economic damage. Companies are increasingly viewing real-time data processing as a prerequisite for operational resilience – especially in a market environment characterized by volatile supply chains, high energy prices, and quality requirements. Thus, real-time capability is the connecting link between integration and adaptability.

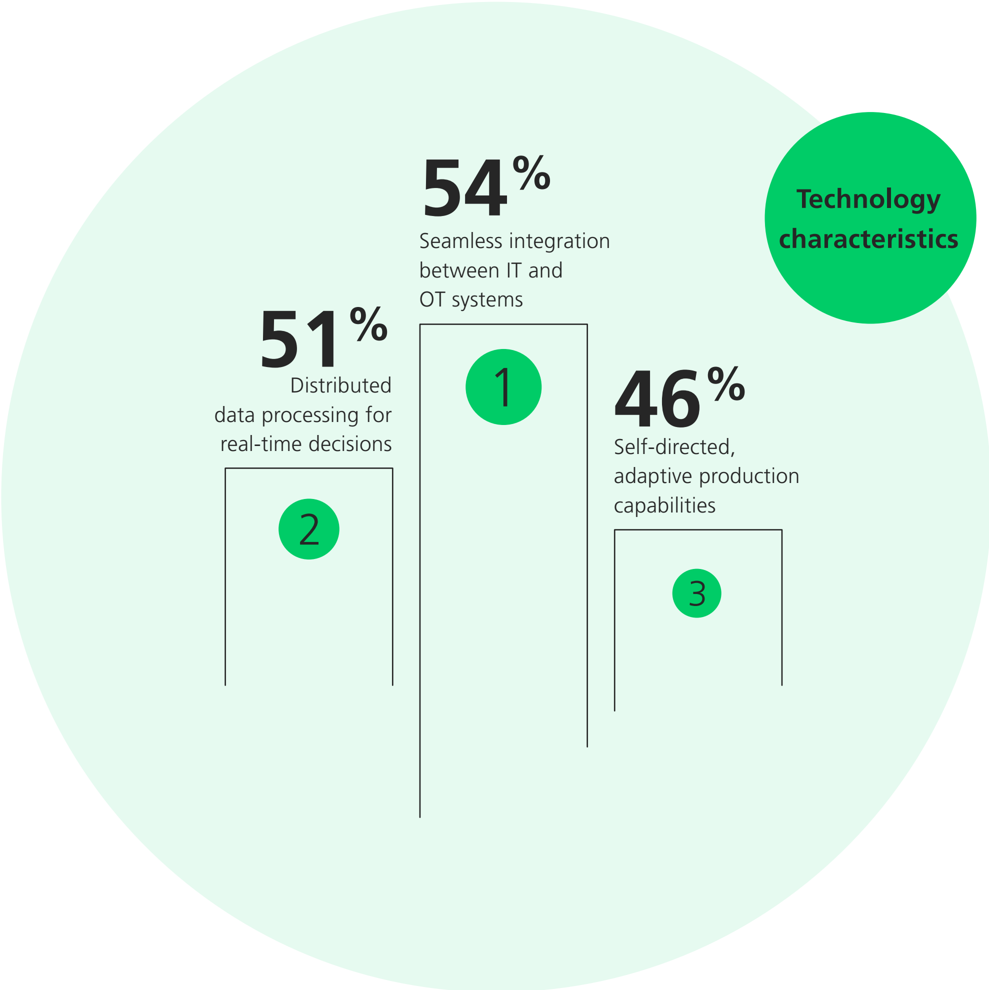


Fig. 32: Key technology characteristics for future-proof production systems / n – 1,206

The perception that adaptive production systems are among the most important features of the future demonstrates a clear qualitative shift in the way companies think. Digitalization is no longer seen merely as a means of achieving transparency, monitoring, and documentation, but as the foundation for systems that continuously adapt to changing conditions. Adaptive systems go beyond traditional automation: They independently analyze deviations, correct parameters within defined limits, and dynamically optimize processes. This brings to the forefront a form of production intelligence that was previously achievable only in highly specialized fields. This approach marks the transformation from static production lines to adaptive, resilient value creation networks. Respondents see in this not only technical potential, but also a strategic lever for ensuring quality, efficiency and flexibility.

2.2.8 Structural hurdles to digital transformation – legacy systems, architectures, and machinery

Although the technological targets are clearly formulated, the survey results also make it evident that their implementation will not be achieved automatically. On the contrary, companies face several deeply entrenched structural hurdles (Figure 33): In first place are legacy infrastructures and the integration of existing systems, which 50 percent of the companies surveyed ranked among their top-3 technical obstacles. In second place is a complex and fragmented system architecture, which 46 percent of companies consider to be one of the most significant obstacles. The third-largest obstacle is considered to be heterogeneous and tightly coupled machine and plant environments (45 percent). These three issues – legacy systems, architectures, and machine parks – constitute the core structural problem facing industry.

The figures cited make it clear that the greatest obstacles to digital transformation lie less in a lack of technologies than in the structural conditions under which these technologies must be implemented. At the same time, the responses reveal that the desired technological targets – real-time capability, IT/OT integration, and adaptive control – are currently failing due to precisely these systemic hurdles.

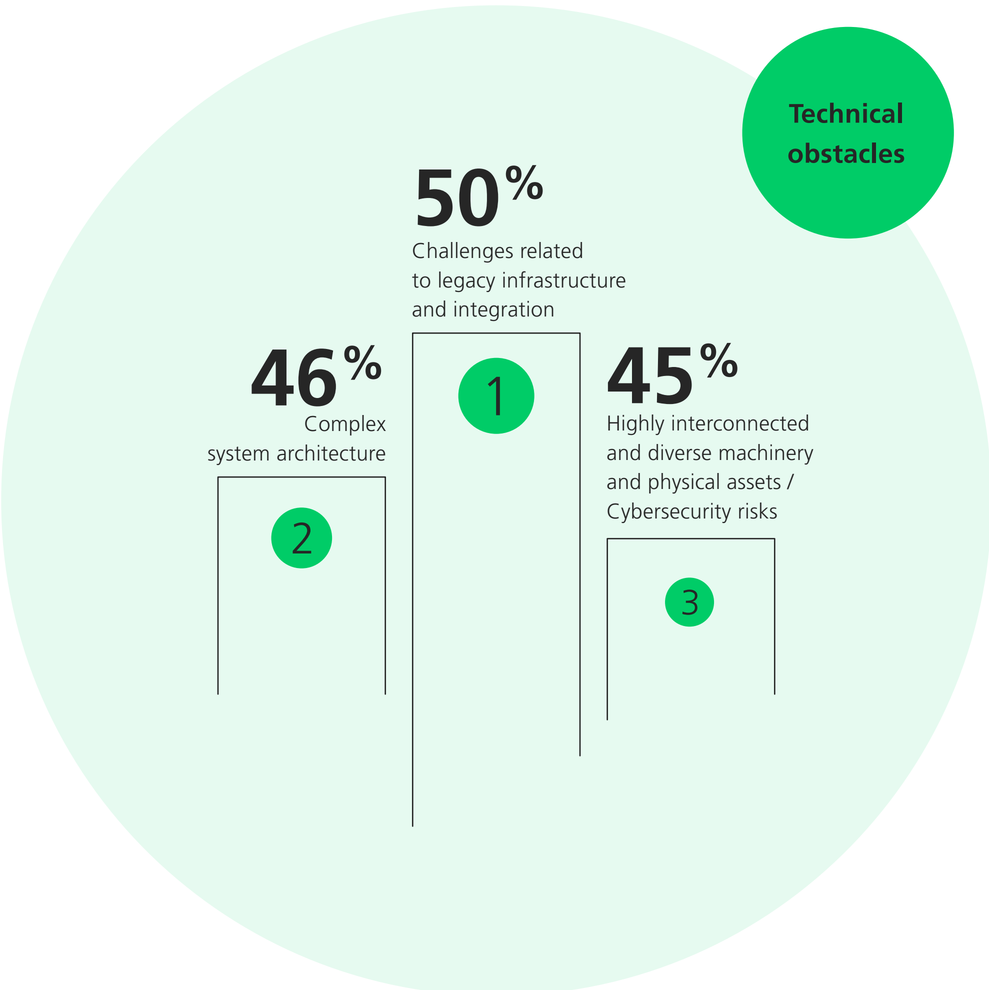


Fig. 33: Key technical obstacles to digitalization aimed at increasing flexibility and scalability in production / n – 1,206

Legacy infrastructures and the effort required for integration – the most frequently cited set of obstacles – point to a fundamental problem faced by many industrial companies: The technological starting point is not a neutral foundation, but rather a historically evolved network of machines and systems. Control systems that have been adapted over decades, proprietary interfaces, and outdated IT systems turn any modernization effort into an intervention in a fragile overall structure. Integration costs rise, harmonization becomes an ongoing task, and the pace of innovation lags behind ambitions. Thus, legacy systems are not only technically limiting but also act as a structural constraint that prevents pilot projects from being scaled up or new architectures from being rolled out quickly.

The complex system architecture – cited as the second-largest hurdle – demonstrates that, today, digitalization is not primarily a technical challenge, but rather an architectural and organizational one. Many companies have legacy system landscapes: Manufacturing Execution System (MES) variants of different generations, various automation solutions, unconnected databases, and historically separate IT and OT domains. This creates a web in which responsibilities are unclear, data flows are hardly standardized, and processes can only be harmonized with great effort. System complexity becomes a structural impediment that slows scalability and makes it difficult to build modular architectures over the long term.

The diversity of machine fleets – cited as the third-largest obstacle – points to a deep-seated infrastructural problem: Many systems are functionally interdependent, closely interconnected, and often not designed in a modular manner. Any modernization carried out at one point may require adjustments to several other components. In addition, there is a heterogeneous landscape of different manufacturers, technologies and interfaces, which makes it extremely difficult to establish consistent data models or interoperable communication protocols. As a result, machine fleets become strategic variables in digitalization, determining the speed, effort, and risk associated with any change to core processes.

2.2.9 Lack of standardization as a strategic risk

It is striking that companies are increasingly recognizing the lack of standardization as a strategic risk. As long as data models, interfaces, and protocols are not standardized, each solution remains a local, one-off project that may be successfully implemented at one plant but is unlikely to be replicable at other sites, in other markets, or with other supply chain partners. The result is a fragmented technology landscape in which pilot projects can be developed quickly, but rarely make the leap into widespread productive use.

When viewed as a whole, a clear pattern emerges. Companies, technological ambitions are more advanced than the maturity of their infrastructures; real-time data processing, IT/OT integration, and modular architectures are recognized as business-critical foundations, but they are held back by proprietary control islands, isolated data silos, and inconsistent architectural principles. This reveals an indicator of maturity: Industry has an increasingly precise vision of future production architectures, while the structural path to achieving this vision is more complex and demanding than purely technological roadmaps suggest.

The tension between ambition and feasibility is further exacerbated by the regulatory framework. With the EU Data Act, the European Union has, for the first time, established a binding framework for accessing and using data from connected products. The EU Data Act has been in force since January 2024 and has been fully applicable since September 2025. It requires manufacturers and operators to provide usage and operational data in an accessible and interoperable form. Thus, interoperability is not only recommended from a technical standpoint but also required by regulation. For companies, this means that proprietary data silos are increasingly becoming a compliance risk, and open, standardized architectures are gaining in importance.

At the same time, through the Digital Product Passport (DPP), the EU is promoting new requirements for transparency and data quality throughout the product lifecycle. The DPP is to become mandatory in various product categories over time and will provide standardized, digitally readable information on a product's origin, composition, and sustainability characteristics. As a result, expectations for consistent, structured and traceable data in the industrial environment are continuing to rise.

In summary, core technologies are clearly prioritized, and companies have a clear vision of a connected, learning-enabled production environment. Therefore, the key challenge is no longer on "if" but on "how fast, how broadly, and how standardized?" The data shows that this question has long since become a strategic importance.

2.2.10 A comparison of international priorities

An international comparison shows that companies worldwide are pursuing similar technological visions, but that their priorities vary depending on their industrial starting point. In established industrialized nations, particularly in the DACH region, the U.S., and the United Kingdom, the seamless integration of IT and OT systems is consistently identified as a key driver for future-proof production systems. It is ranked among the three most important characteristics by 57 percent of respondents in the DACH region, 63 percent in the U.S., and 69 percent in the United Kingdom. Closely related to this, in these countries, distributed data processing (DDP), where multiple computers at different locations communicate over a network, is ranked highly for real-time decision-making. It is given particularly high priority in the United Kingdom (58 percent) and the United States (53 percent). In all three regions, this picture is complemented by a growing interest in predictive self-optimization, which also frequently ranks among the top 3 (Figure 34.1).

In contrast, in several emerging markets, a broader, less hierarchical priority profile is emerging. In China, interoperability between different manufacturing systems is most frequently included in the top 3, at 47 percent. This is followed by distributed data processing for real-time decisions, self-directed and adaptive production capabilities, and predictive self-optimization of production processes, each at 45 percent, which are thus closely aligned and reflect a broad technological requirement profile (Figure 34.2). In addition, ultra-low latency for real-time decision-making also plays a role, with 39 percent selecting it as one of the most important characteristics. This figure is slightly lower, but it indicates that, in dynamic and high-frequency production environments, short response times are seen as an additional competitive advantage.

Key technological characteristics by country

1

57% Seamless integration between IT and OT systems

69% Seamless integration between IT and OT systems

63% Seamless integration between IT and OT systems

47% Interoperability between different manufacturing systems

50% Distributed computing for real-time decision-making / Seamless integration between IT and OT systems

57% Self-directed, adaptive production capabilities

2

48% Self-directed, adaptive production capabilities

58% Distributed computing for real-time decision-making

53% Distributed computing for real-time decision-making

45% Self-directed, adaptive production capabilities / Predictive self-optimization of production processes / Distributed computing for real-time decision-making

46% Interoperability between different manufacturing systems / Self-directed, adaptive production capabilities

49% Distributed computing for real-time decision-making

3

47% Distributed computing for real-time decision-making

43% Predictive self-optimization of production processes

47% Predictive self-optimization of production processes

42% Virtual simulation and optimization of manufacturing systems

44% Virtual simulation and optimization of manufacturing systems

45% Seamless integration between IT and OT systems

Fig. 34.1: Key technological characteristics for future-proof production systems by country / n – 1,206

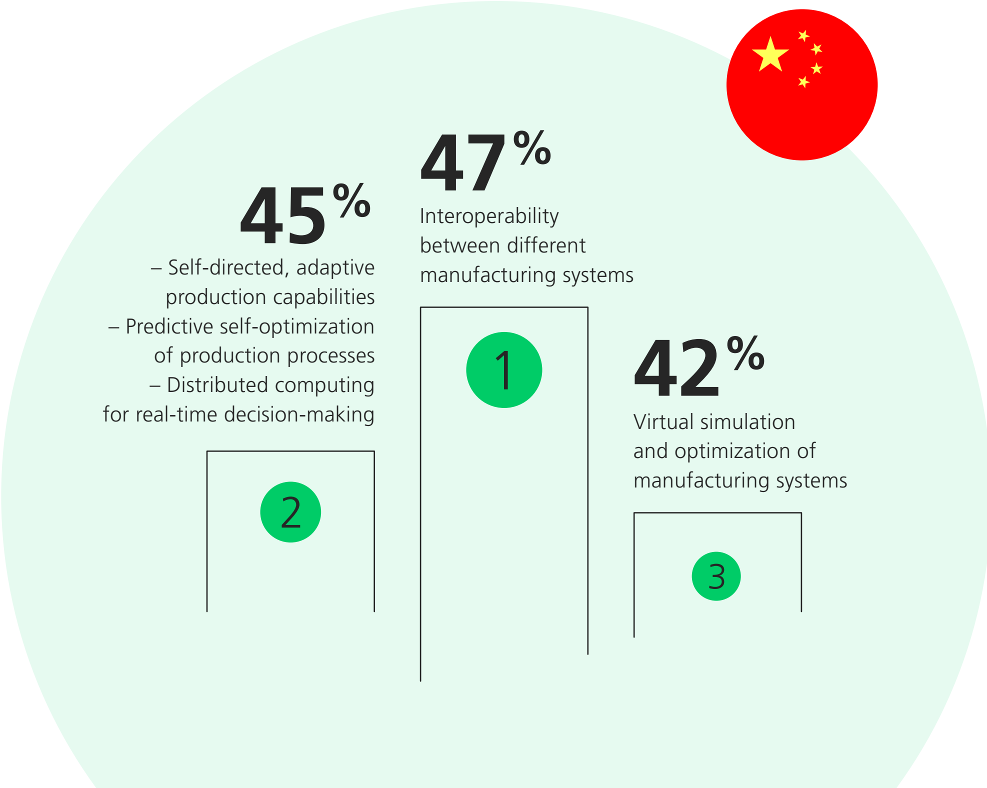


Fig. 34.2: Key technological characteristics for future-proof production systems – China / n – 1,206

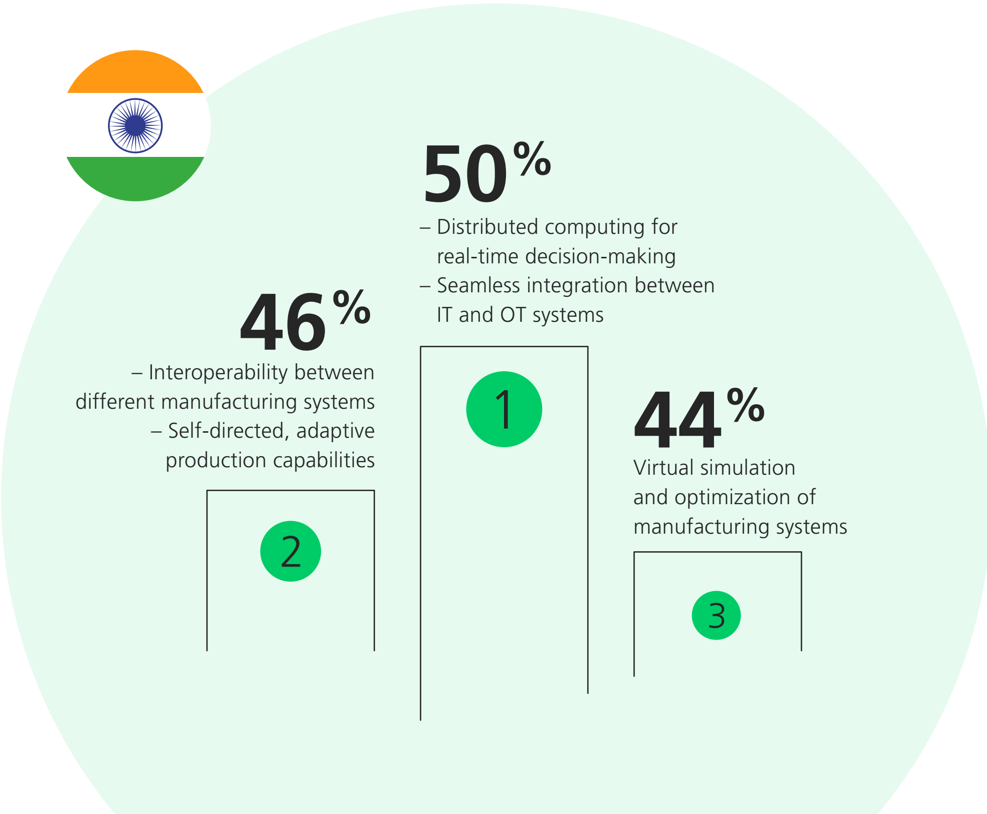


Fig. 34.3: Key technological characteristics for future-proof production systems – India / n – 1,206

India exhibits a similar pattern (Figure 34.3), with both IT/OT integration and real-time data processing being selected as top-3 features by 50 percent of respondents, while interoperability and adaptive production processes are also highly rated, each at 46 percent. In Mexico, by contrast, self-directed, adaptive production capabilities dominate, clearly taking first place at 57 percent, followed by real-time data processing (46 percent) and IT/OT integration (45 percent).

A differentiated regional pattern can also be observed when it comes to technical obstacles (Figure 35). In the DACH region, systemic legacy issues dominate: Legacy infrastructures and integration efforts are selected as the top 3 greatest obstacles by 27 percent, complex architectures by 26 percent, and a lack of data integration by 21 percent. In the U.S., by contrast, cybersecurity risks rank first at 56 percent, closely followed by legacy systems (55 percent); architecture complexity also carries significant weight at 45 percent. In the United Kingdom, integration and architecture issues similarly dominate the picture.

In contrast, China, India, and Mexico exhibit a different pattern: Here, highly interconnected and diverse machine and plant environments are particularly frequently cited as among the greatest technical challenges – ranking among the top 3 at 50 percent in China, 51 percent in India, and 52 percent in Mexico. These issues are closely linked to the high level of vertical integration and the wide range of technologies that characterize industrial value chains in these regions.

This international comparison makes it clear that, although the technological ambitions of industries are moving in the same direction, their priorities are strongly influenced by their respective structural starting points. A clear pattern emerges in Western industrialized nations. There, the harmonization of historically established IT/OT landscapes is the key driver of digital transformation. The high priority placed on IT/OT integration and real-time data availability in the DACH region, the U.S., and the United Kingdom indicates that these markets are primarily focused on making existing systems consistent, transparent, and controllable. Therefore, their digital target visions are fundamentally based on the modernization, consolidation, and end-to-end integration of heterogeneous architectures.

Taken as a whole, the international results show that, while the same end state is being pursued worldwide – namely, flexible, interoperable, and learning-capable production systems – the paths to achieving this goal vary greatly. Each region has its own starting point and must shape digital transformation in line with its specific industrial structures: By harmonizing legacy architectures, by managing technological diversity, or by ensuring digital resilience in highly networked manufacturing environments.

Key technical obstacles by country

1

27% Challenges related to legacy infrastructure and integration

58% Challenges related to legacy infrastructure and integration

56% Cybersecurity risks

50% Highly interconnected and diverse machinery and physical assets

51% Highly interconnected and diverse machinery and physical assets

52% Highly interconnected and diverse machinery and physical assets

2

26% Complex system architecture

51% Complex system architecture

55% Challenges related to legacy infrastructure and integration

46% Complex system architecture

49% IT/OT integration

50% Challenges related to legacy infrastructure and integration

3

21% Lack of data integration

44% Cybersecurity risks

45% Complex system architecture

44% Challenges related to legacy infrastructure and integration

47% Cybersecurity risks

42% Complex system architecture

Fig. 35: Key technical obstacles to digitalization to increase flexibility and scalability in production by country / n – 1,206

2.2.11 People and organization

Core competencies and existing skills gaps

The analysis of the competence and organizational dimensions reveals an overall mixed but clearly identifiable pattern: The majority of companies possess basic digitalization skills; at the same time, there are significant gaps in specialized competencies and in the confident use of new technologies. For example, 52 percent of companies report that qualified machine programmers – such as PLC experts – are predominantly or highly available. In contrast, 45 percent consider availability to be limited, while 3 percent report a clear lack of availability (Figure 36).

A divided picture also emerges when it comes to the workforce's willingness to embrace change. Overall, 50 percent of employees indicate agreement or strong agreement, while around 24 percent express a negative attitude. A further 26 percent indicate a neutral stance (Figure 37).

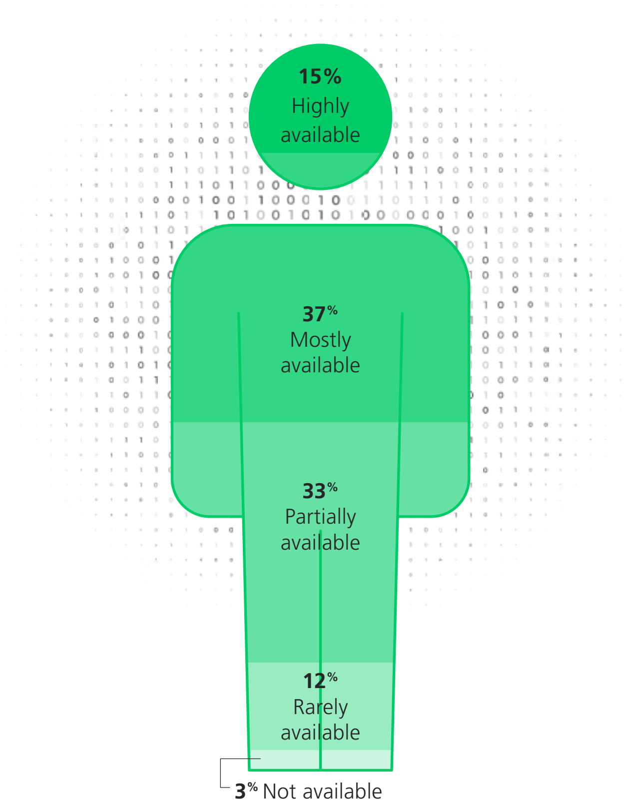


Fig. 36: Availability of qualified PLC programmers for machine control within the company / n – 1,206

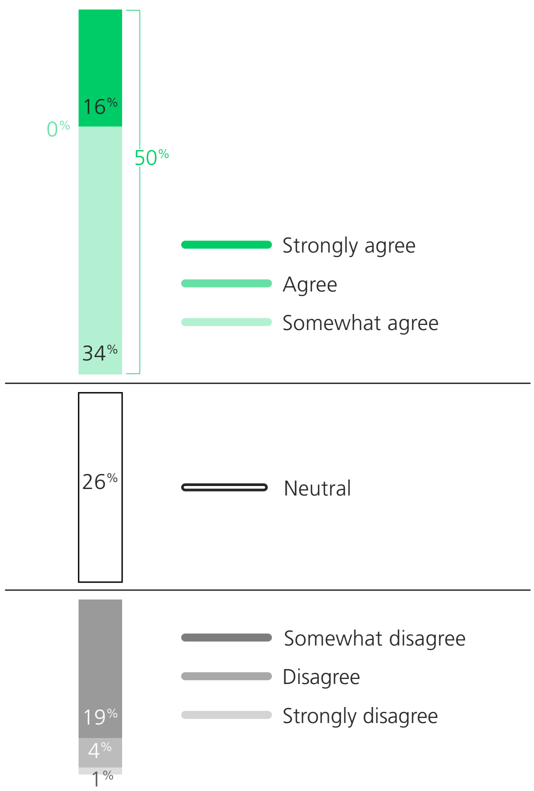


Fig. 37: Willingness of the workforce to adapt to new production systems such as matrix production / n – 1,206

The situation is similar when it comes to working with software-based production systems: 50 percent of employees feel confident or very confident, while 23 percent express uncertainty. 27 percent neither agree nor disagree (Figure 38).

This pattern is repeated when it comes to skills for implementing and operating digital solutions: 50 percent believe they have sufficient skills, 23 percent report shortcomings, and 27 percent remain neutral (Figure 39). The workforce’s ability to integrate digital technologies into day-to-day operations also follows this trend: 52 percent somewhat or strongly agree, 23 percent somewhat disagree, and 25 percent remain neutral (Figure 40).

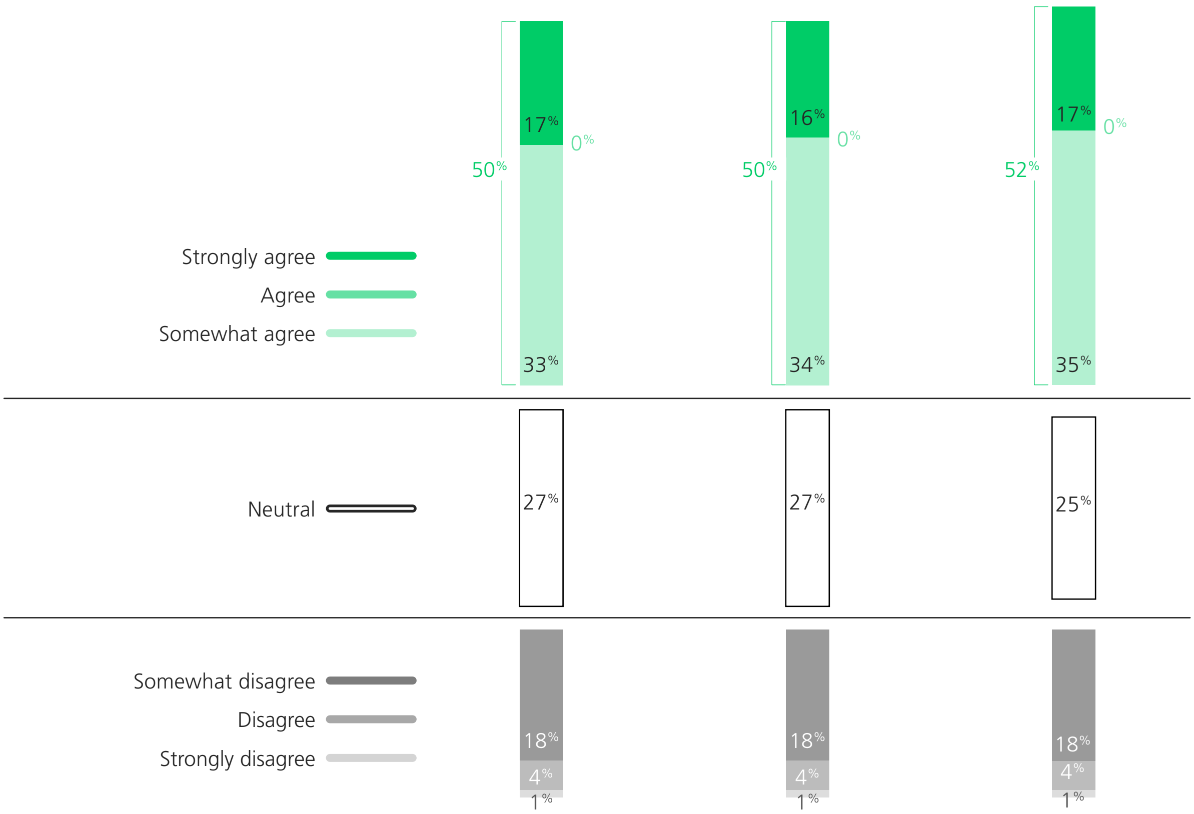


Fig. 38: Employees’ confident use of software-based production systems / n – 1,206

Fig. 39: Workforce competencies for implementing and operating new digital production solutions / n – 1,206

Fig. 40: Employees’ ability to integrate digital technologies into day-to-day operations / n – 1,206

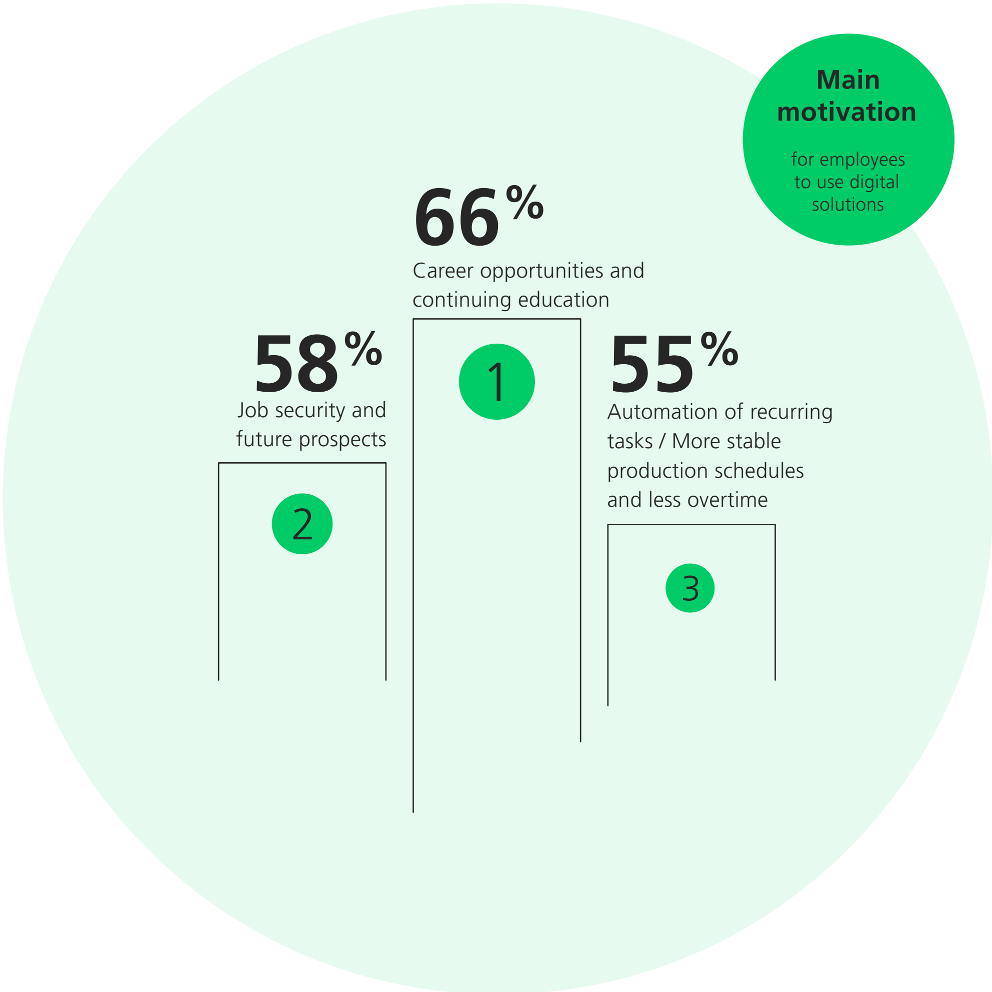


Fig. 41: Main motivators for employees to use new digital production solutions / n – 1,206

2.2.12 Motivation and personal drivers of digitalization

In contrast, the motivational factors are very clear. 66 percent cite career opportunities and further training as one of their three most important drivers, followed by 58 percent for job security and future orientation. Tangible workload reduction effects are also important: 55 percent mention the automation of recurring tasks, as well as more stable production schedules and fewer overtime hours (Figure 41). The biggest concerns reflect the downside of these developments: 50 percent cite job loss or relocation as one of the three most significant risks, 48 percent fear the devaluation of existing skills, and 45 percent each view a lack of digital skills or unclear roles as major negative factors (Figure 42).

Finally, when asked which roles should be most responsible for driving digital transformation, a clear leadership focus emerges (Figure 43): 49 percent of respondents included the CTO or Technical Director among their top 3, followed by the Production Manager (46 percent) and the CIO (45 percent).

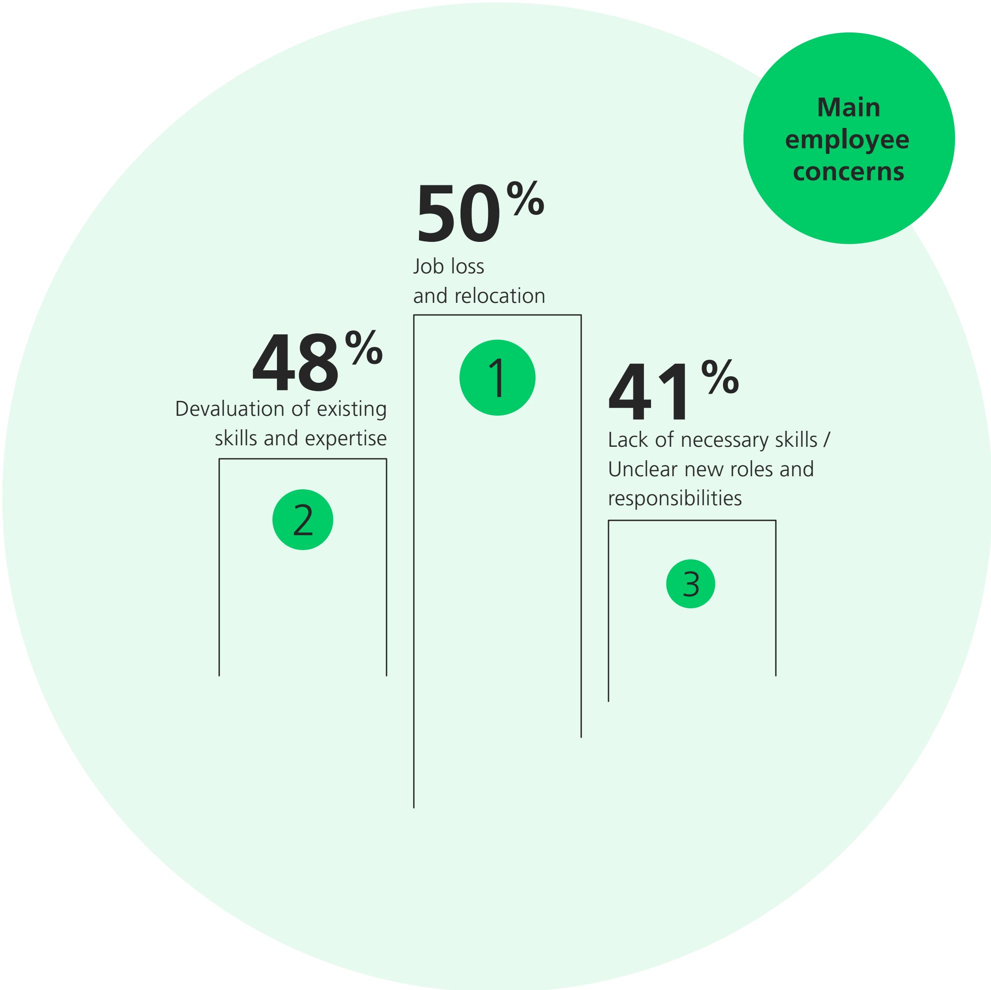


Fig. 42: Main employee concerns regarding new digital solutions in production / n – 1,206

In summary, the results make it clear that the success of digital transformation depends less on technological capabilities than on the organization's ability to engage people along the way. While, overall, the workforce demonstrates a fundamental willingness to embrace new production systems, it is also evident that this willingness is not always supported by sufficient skills or confidence in using digital technologies. In many places, digitalization is met with workforces that are caught between openness and uncertainty: While a substantial proportion of employees view new technologies positively in principle, a significant number feel neither sufficiently empowered nor clearly defined in their roles. This ambivalence is less an expression of a lack of motivation than an indication that systematic skills development strategies have not yet been established in all companies.

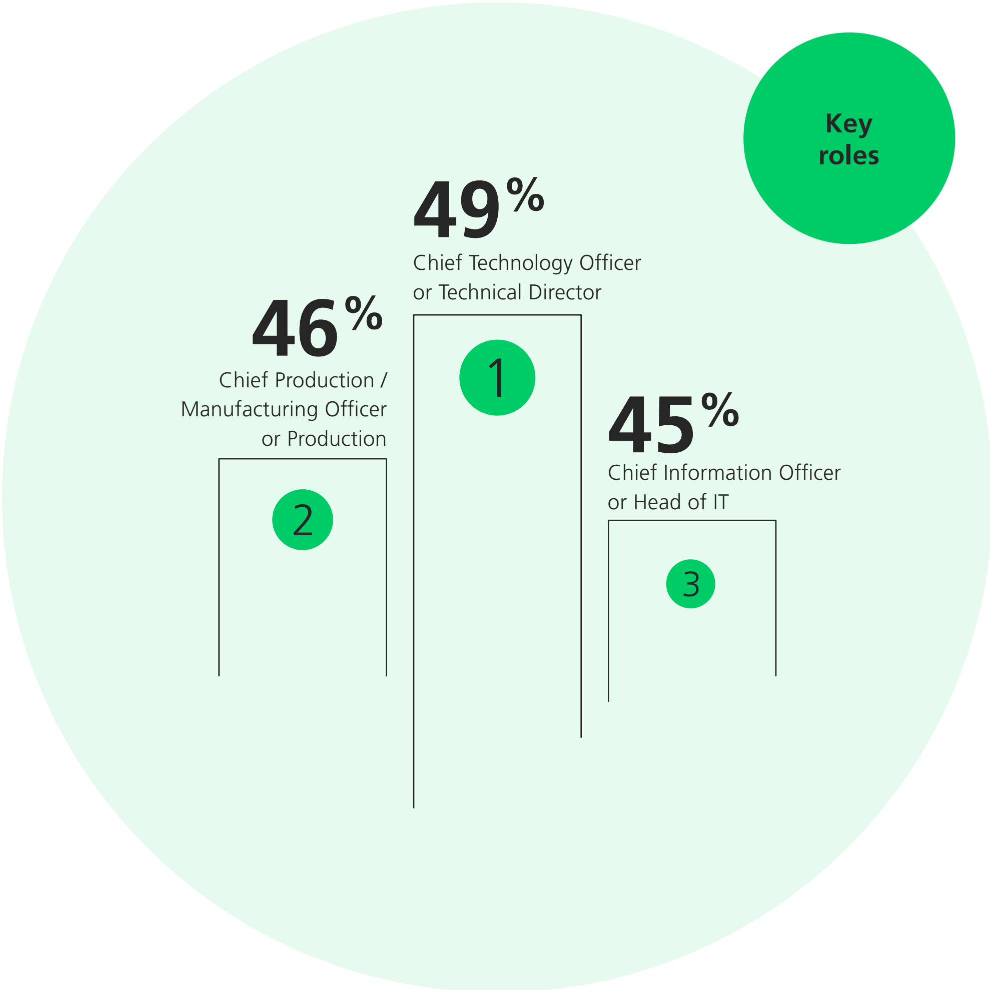


Fig. 43: Assessment of key roles for overseeing and managing production digitalization / n – 1,206

The analysis of the motivation and concern profiles shows very clearly that employees are most likely to accept digital technologies when they see a personal benefit and are given a clear outlook. Continuing education, opportunities for professional development, and a stable vision of the future are perceived as the strongest drivers. Therefore, digitalization is not primarily experienced as a technical innovation, but rather as an individual opportunity when it is associated with the prospect of enhanced skills, job security, and reduced workload. At the same time, resistance arises primarily when digital changes create uncertainty, for example due to unclear roles, potential loss of skills, or concerns that automation will jeopardize one's own job. These patterns of perception show that motivation and resistance are closely linked and shaped by the same fundamental questions: What does this change mean for me personally? Am I adequately prepared for this future?

2.2.13 Digital transformation as a shared leadership and organizational responsibility

The results also clearly show that this responsibility for digital transformation does not lie with a single function, but is broadly anchored throughout the organization. The fact that CTOs, production managers and CIOs were mentioned with equal frequency underscores the importance of an integrated leadership approach. The digitalization of production is neither a purely technological project nor an isolated production task, but rather a combination of technical vision, operational implementation, and IT architecture expertise. This makes it clear that the development of a learning-capable and modular production landscape will only succeed if strategic and operational leadership work together and view the transformation as an organizational task.

Taken as a whole, the results show that people are not merely a supporting factor in digitalization, but rather its true driving force. Many companies have a good understanding of the technical side of the transformation. However, the speed at which new production solutions can be established and scaled depends largely on the ability to systematically develop expertise, communicate clear future prospects, address concerns early on, and clearly define responsibilities. The digital transformation of the manufacturing is a matter of organizational

To what extent are qualified machine control programmers available at your company?

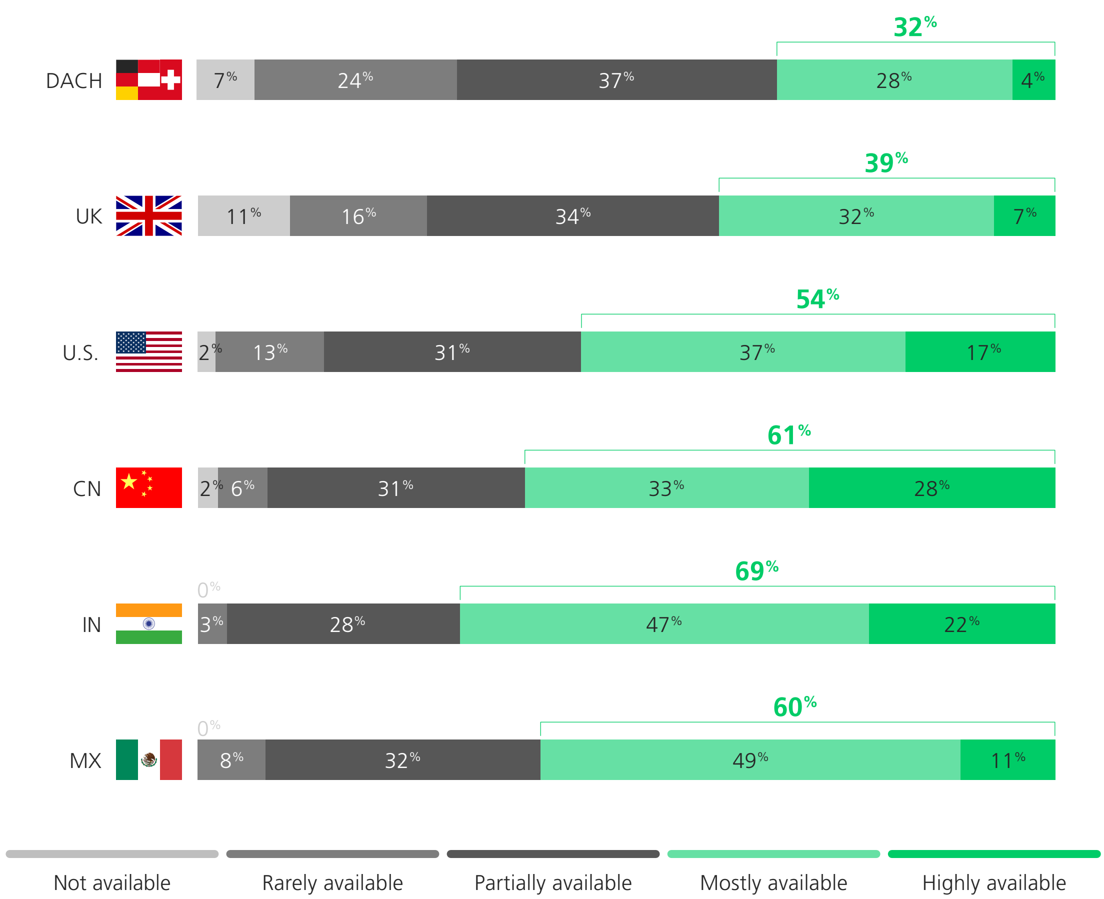


Fig. 44: Availability of qualified PLC programmers for machine control within the company by country / n – 1,206

maturity – and this maturity is largely determined by skills, trust, and leadership, not by machines, sensors, or software.

An international comparison shows that the human resources and organizational prerequisites for digital production systems vary greatly around the world. This is particularly evident when it comes to the availability of qualified machine programmers (Figure 44). While the DACH region has a relatively strong, though not fully secure, skilled-worker base, other countries report significantly more heterogeneous situations or more pronounced shortages. The proportion of companies that have "mostly" or "highly" available expertise varies significantly across countries, indicating that the starting point for implementing software-based production systems differs considerably from region to region.

Our workforce is ready and willing to adapt to new production systems (e.g., matrix production).

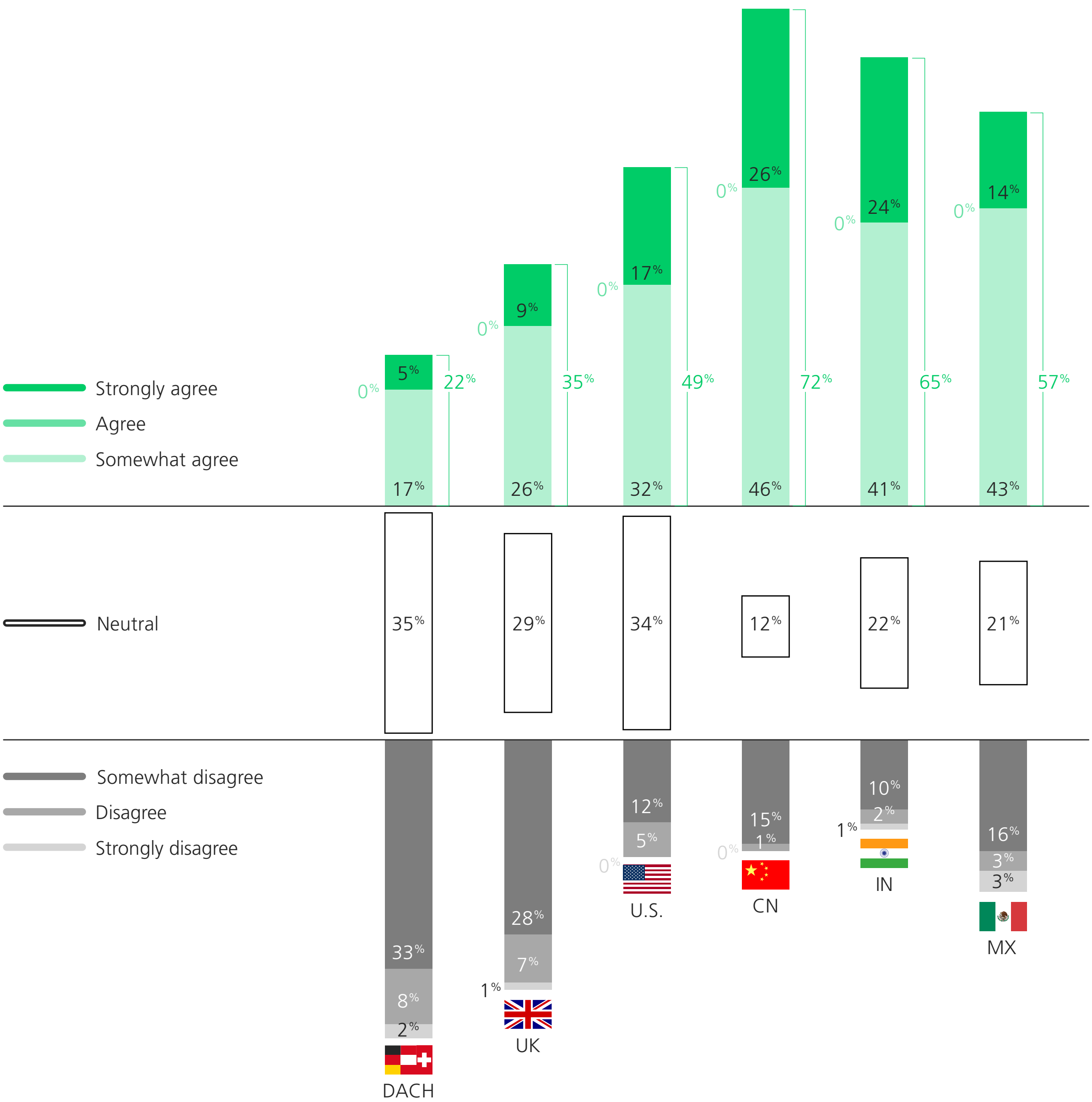


Fig. 45: Willingness of the workforce to adapt to new production systems / n – 1,206

Key motivators across countries

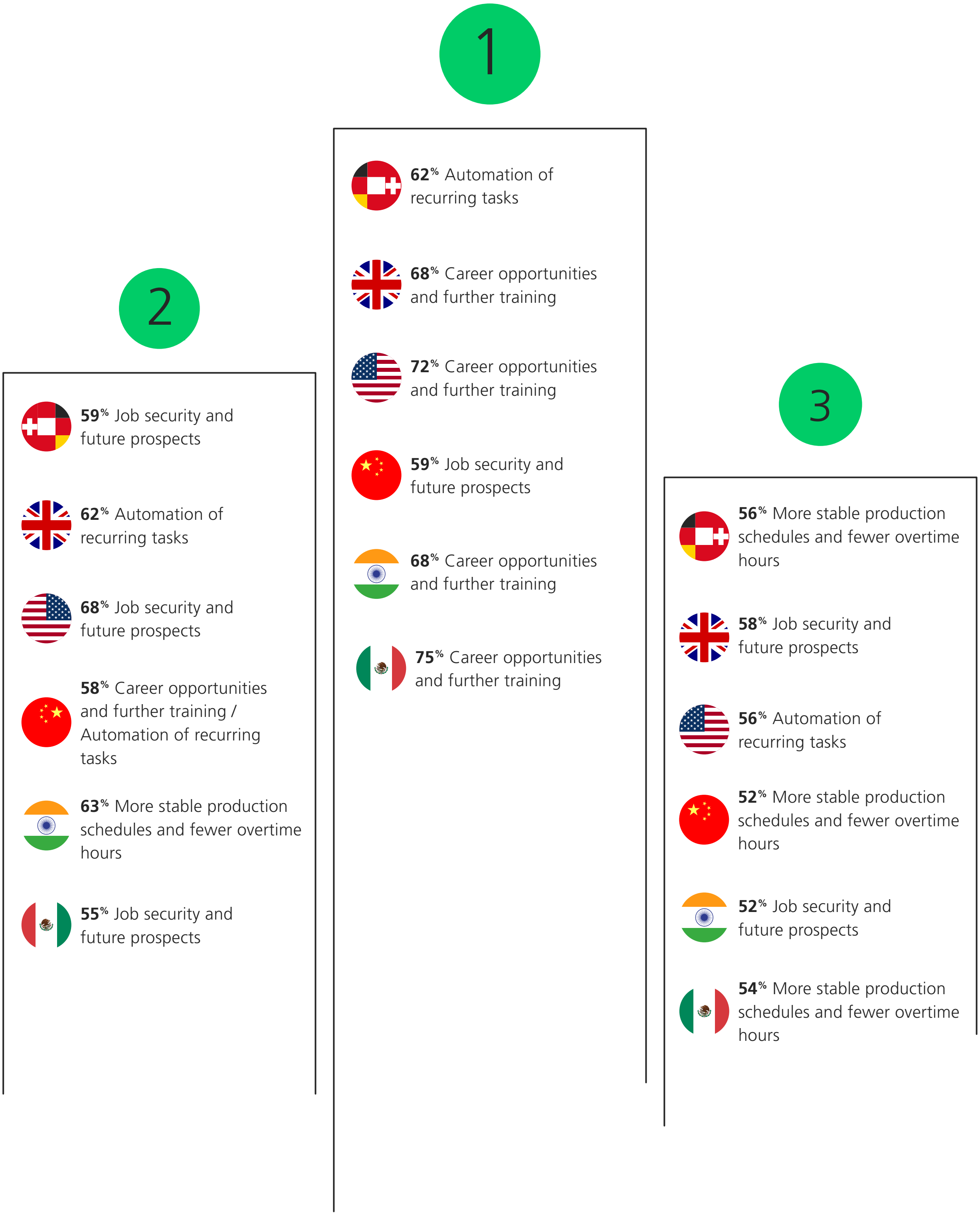


Fig. 46: Key motivators for employees to use new digital solutions in production by country / n – 1,206

Employees' willingness to embrace change also varies across countries (Figure 45). In the DACH region, the attitude is rather cautious and often hesitant, with agreement and neutrality closely aligned. Other regions tend to show higher or more pronounced levels of agreement, while at the same time, uncertainties and doubts remain evident among many employees. The use of software-based systems, trust in digital tools, and self-assessment of the necessary skills also vary by region, which can be attributed to differences in skill levels, training models, and experience backgrounds.

When it comes to the motivating factors for the use of new digital solutions in production, on the other hand, the picture is largely consistent: In nearly all countries, opportunities for further training, prospects for professional development, and job security are among the most important drivers for the acceptance of digital technologies. In many regions, tangible reductions in the workload of day-to-day work – for example, through the automation of monotonous tasks or more stable planning – are also regularly cited as among the three most important motivators (Figure 46).

On the other hand, concerns and resistance are strongly influenced by cultural and labor market policy frameworks. Fear of job loss, concern about the devaluation of one's own skills, or uncertainty about new roles and responsibilities are among the most important concerns in nearly all the countries surveyed – but they differ in their intensity and prioritization (Figure 47).

The question of which roles drive digitalization also reveals regional patterns: While in some countries technology-focused roles such as CTO or CIO predominate, in other regions production management or operations play a more prominent role. The top-3 responses in each case reveal where responsibility for digital transformation is anchored within the organization – and which leadership cultures shape the modernization of production (Figure 48).

2.2.14 Global differences in motivations, concerns, and responsibilities

The international comparison makes it clear that the role of people as a success factor in digitalization varies around the world. Countries with well-developed training structures and established industrial skill profiles have a more stable foundation for implementing digital production systems. Where skilled workers are available and employees feel confident using digital tools, the transformation process is noticeably more uniform and is implemented at a faster pace.

In countries where skill levels vary or where advanced management skills are less common, digitalization more quickly becomes a matter of organizational structure. The pace of transformation depends more on how rigorously companies pursue employee qualification, retraining, and skills development. Uncertainties or neutral attitudes indicate that, in many places, expectations are still unclear – a challenge that is exacerbated by a lack of role models or insufficient visibility of new job profiles.

Key employee concerns across countries

1

- **56%** Job loss and relocation
- **58%** Job loss and relocation
- **55%** Job loss and relocation
- **56%** Unclear new roles and responsibilities
- **50%** Devaluation of existing skills and expertise
- **55%** Job loss and relocation

2

- **39%** Devaluation of existing skills and expertise / Lack of necessary skills / Skepticism about the actual benefits
- **44%** Devaluation of existing skills and expertise
- **49%** Devaluation of existing skills and expertise
- **53%** Devaluation of existing skills and expertise
- **48%** Job loss and relocation
- **51%** Devaluation of existing skills and expertise

3

- **35%** Unclear new roles and responsibilities
- **44%** Lack of necessary skills
- **40%** Lack of necessary skills
- **49%** Loss of control and autonomy
- **44%** Lack of necessary skills
- **40%** Unclear new roles and responsibilities

Fig. 47: Main employee concerns regarding new digital solutions in production by country / n – 1,206

Assessment of key roles across countries

1

52% Chief Information Officer or Head of IT

51% Chief Technology Officer or Technical Director

56% Chief Technology Officer or Technical Director

46% Chief Technology Officer or Technical Director / Chief Information Officer or Head of IT

48% Chief Production / Manufacturing Officer or Production Manager

57% Chief Production / Manufacturing Officer or Production Manager

2

43% Chief Technology Officer or Technical Director

48% Chief Information Officer or Head of IT

54% Chief Information Officer or Head of IT

43% Chief Production / Manufacturing Officer or Production Manager

41% Chief Technology Officer or Technical Director

56% Chief Technology Officer or Technical Director

3

40% Chief Production / Manufacturing Officer or Production Manager / Chief Operating Officer or Head of Operations

46% Chief Operating Officer or Head of Operations

43% Chief Production / Manufacturing Officer or Production Manager

38% Chief Digital Officer or individual with digital responsibilities

39% Chief Executive Officer, Board Member or Managing Director

52% Chief Operating Officer or Head of Operations

Fig. 48: Assessment of key roles for overseeing and managing production digitalization by country / n – 1,206

Although motivation and concern profiles are similar across national borders, their weighting differs significantly. While opportunities for further training and career development have a positive impact everywhere, the intensity of concerns about automation or the loss of skills varies greatly by region. In labor markets with higher job insecurity or lower skill levels, these fears are more pronounced. In contrast, in more stable, more highly regulated work environments, issues such as professional development opportunities or workload reduction take greater prominence.

The identification of leadership roles also reflects country-specific organizational models. In technology-driven markets, the CTO and CIO clearly play a more prominent leadership role. In production-oriented regions, responsibility lies more in the operational area. Thus, digital transformation always follows cultural patterns of leadership: It is successfully established when technology and production work together, regardless of who formally holds the reins.

Overall, the cross-country comparison shows that, when it comes to people and organizations, digitalization does not work in the same way everywhere, but is highly context-dependent. The path to digitally competent, motivated, and transformation-ready workforces is central everywhere, but the starting points, obstacles, and levers vary significantly. Successful companies are those that recognize and address these differences and place the human component of transformation at the heart of their strategic development.

2.2.15 Obstacles and risks

Operational and organizational obstacles to implementation

The analysis shows that, from the perspective of companies, the main obstacles to the adoption of modular, scalable and flexible production systems are structural, organizational and economic in nature. When it comes to operational obstacles, the complexity of implementation and deployment is clearly at the forefront: 55 percent of respondents selected this aspect as one of the three most important obstacles. This makes it clear that it is not individual technologies but the overall coordination of architecture, processes, and organization that is perceived as the greatest challenge.

Lack of standardization and lack of best practices are also frequently mentioned, with 43 percent placing these among their top-3 concerns. Companies view this as a key scaling problem, as solutions are often highly context-dependent and can only be transferred to other locations with a great deal of customization. In addition, 42 percent of respondents identified a lack of collaboration between departments as a significant barrier (Figure 49). This response makes it clear that functional silos and unclear interfaces between IT, production, engineering, and management significantly complicate the implementation of modular production approaches.

Economic and organizational risks emerge even more clearly when respondents are asked about the biggest obstacles to advanced digital and software-controlled manufacturing solutions. Here, high implementation and conversion costs clearly rank first among the

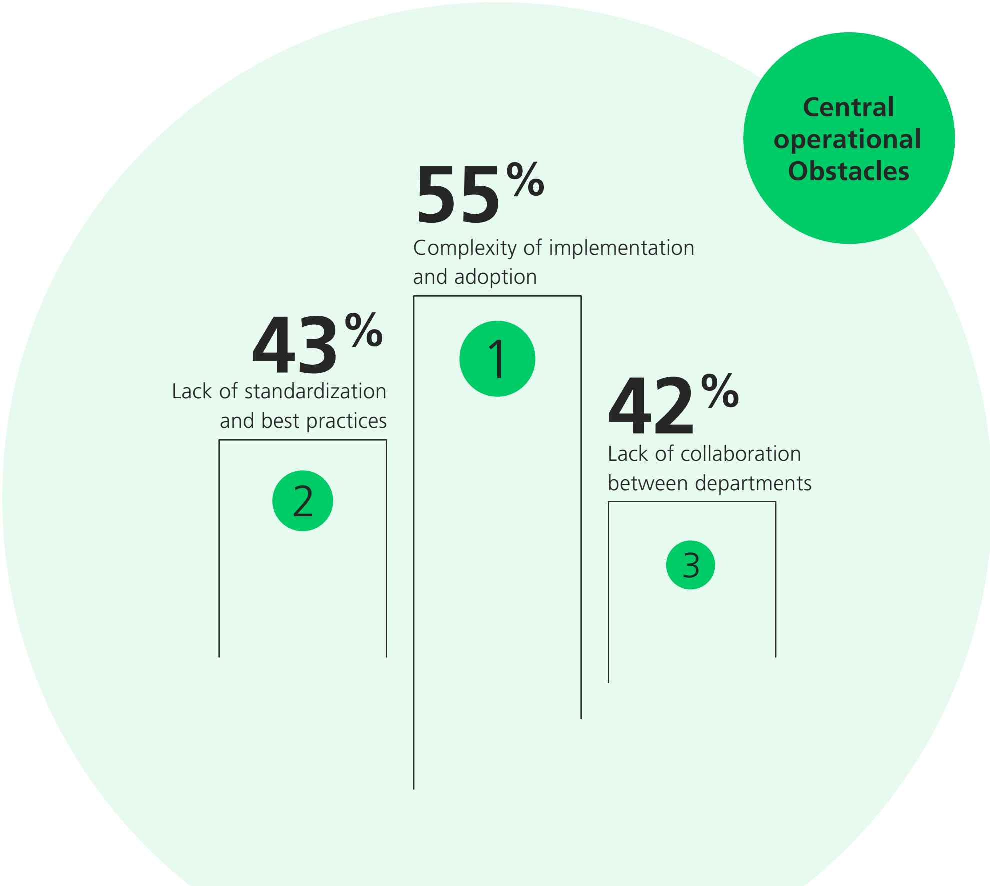


Fig. 49: Key operational obstacles to the adoption of modular, scalable, and flexible production systems / n – 1,206

top-3 responses, selected by 60 percent. Respondents identified investment requirements, conversion costs, and ongoing expenses as the main obstacles to decision-making.

In second place is the fear of major operational disruptions during the transition, which 45 percent of companies consider to be one of the most significant risks. Production disruptions, quality issues, or delivery delays are perceived as real risks that are difficult to compensate for, especially during ongoing operations. In addition, 43 percent cite resistance to change at various organizational levels as a significant obstacle (Figure 50). This response shows that risks are not only of a technical or financial nature, but are deeply rooted in organizational routines, responsibilities, and power structures.

The results make it clear that the obstacles and risks associated with digital transformation stem less from a lack of technological knowledge than from the complexity of implementation in a real-world operational context. The high prioritization of implementation complexity makes it clear that modular and scalable production systems are not viewed as isolated technology projects, but rather as far-reaching changes to existing architectures, processes, and organizational models. Therefore, digitalization does not merely mean introducing new software or machines, but rather a comprehensive reorganization of industrial value creation.

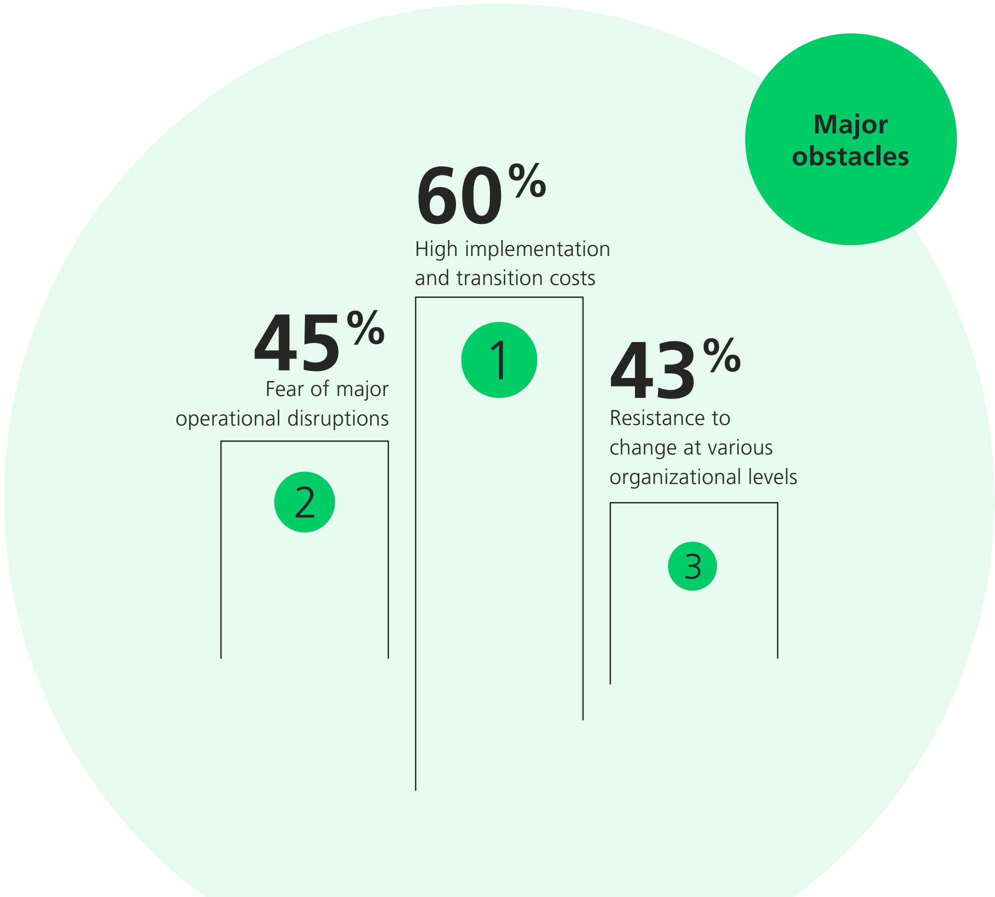


Fig. 50: Major obstacles to the implementation of advanced digital and software-controlled manufacturing solutions / n – 1,206

The significance of the lack of standards and best practices points to a structural maturity gap between the technological vision and operational reality. As long as there are no generally accepted reference architectures, data models, and procedural patterns, each implementation will remain an individual project with limited transferability. This not only increases effort but also amplifies uncertainties when making investment decisions.

2.2.16 Economic risks and internal company resistance

Economic risks – particularly costs and potential operational disruptions – act as amplifiers of these uncertainties. Companies are increasingly weighing digital innovation against stability, delivery reliability, and efficiency. Where production disruptions can have existential consequences, change is inevitably approached with caution. The additional resistance mentioned at the organizational level shows that transformation reaches its limits where responsibilities remain unclear or where changes are perceived as a threat to existing roles.

When viewed as a whole, it becomes clear that the key risks associated with digitalization lie less in the technology itself than in the organization's ability to manage complexity, mitigate risks, and actively shape change. Digital transformation thus becomes a strategic leadership task in which economic, technical, and cultural aspects are closely interlinked.

The international comparison shows that the fundamental obstacles to digital transformation are similar worldwide, but that their weighting depends heavily on the specific industrial context. In the DACH region, the U.S., and the United Kingdom, the complexity of implementation and deployment consistently dominates when it comes to the adoption of modular production systems (DACH 63 percent, U.S. 66 percent, United Kingdom 64 percent). In addition, a lack of standardization and reluctance to change existing functional systems are often cited among the top-3 obstacles (Figure 51.1).

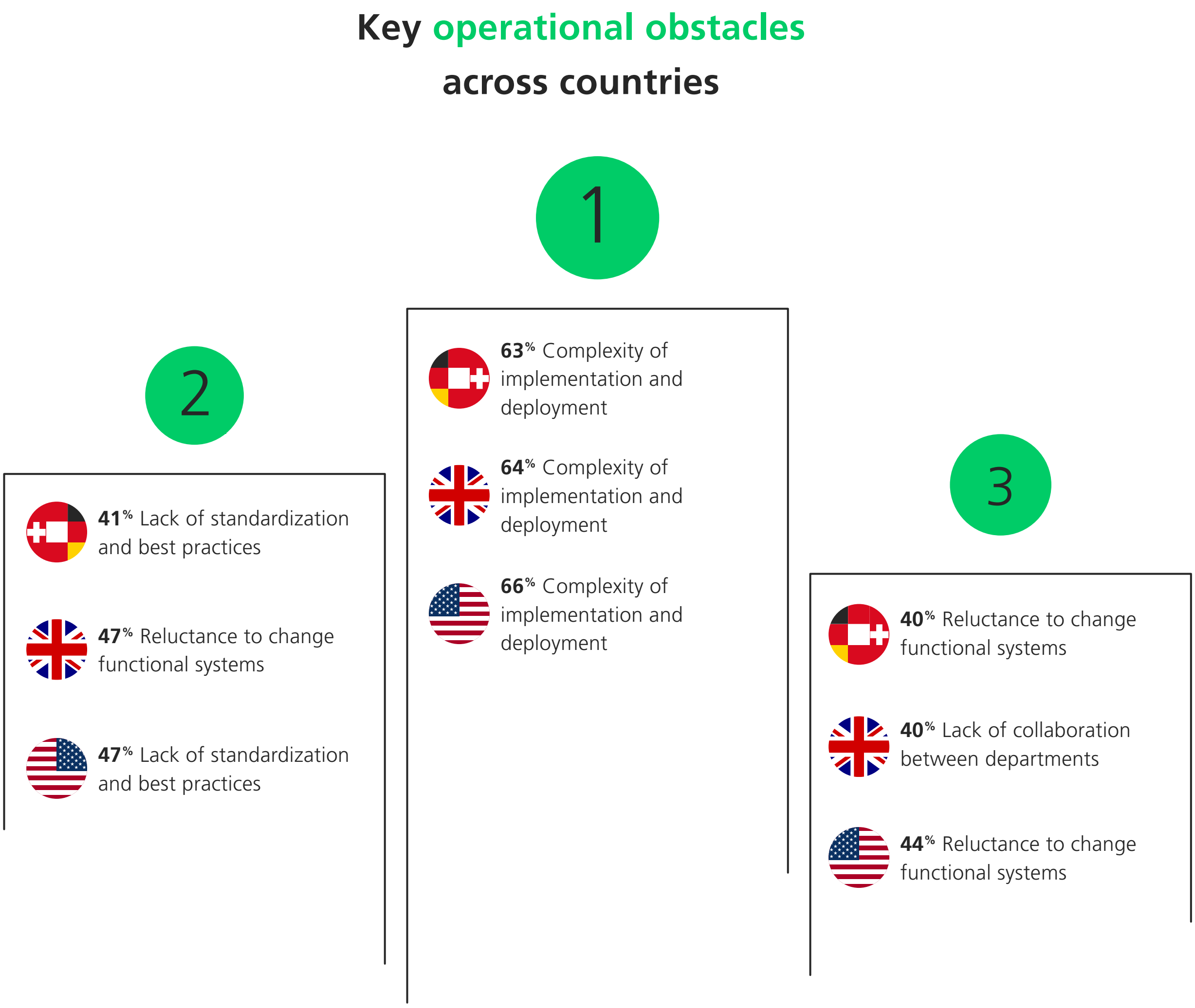


Fig. 51.1: Key operational obstacles to the adoption of modular, scalable, and flexible production systems by country (DACH, UK, U.S.) / n – 1,206

In China, India, and Mexico, the focus is shifting. Here, a lack of collaboration between departments, overly complex implementation and rollout, and insufficient standards are particularly frequently cited as key obstacles (Figure 51.2). These patterns reflect production environments characterized by a high degree of vertical integration, closely interconnected systems, and complex organizational structures.

Key operational obstacles across countries

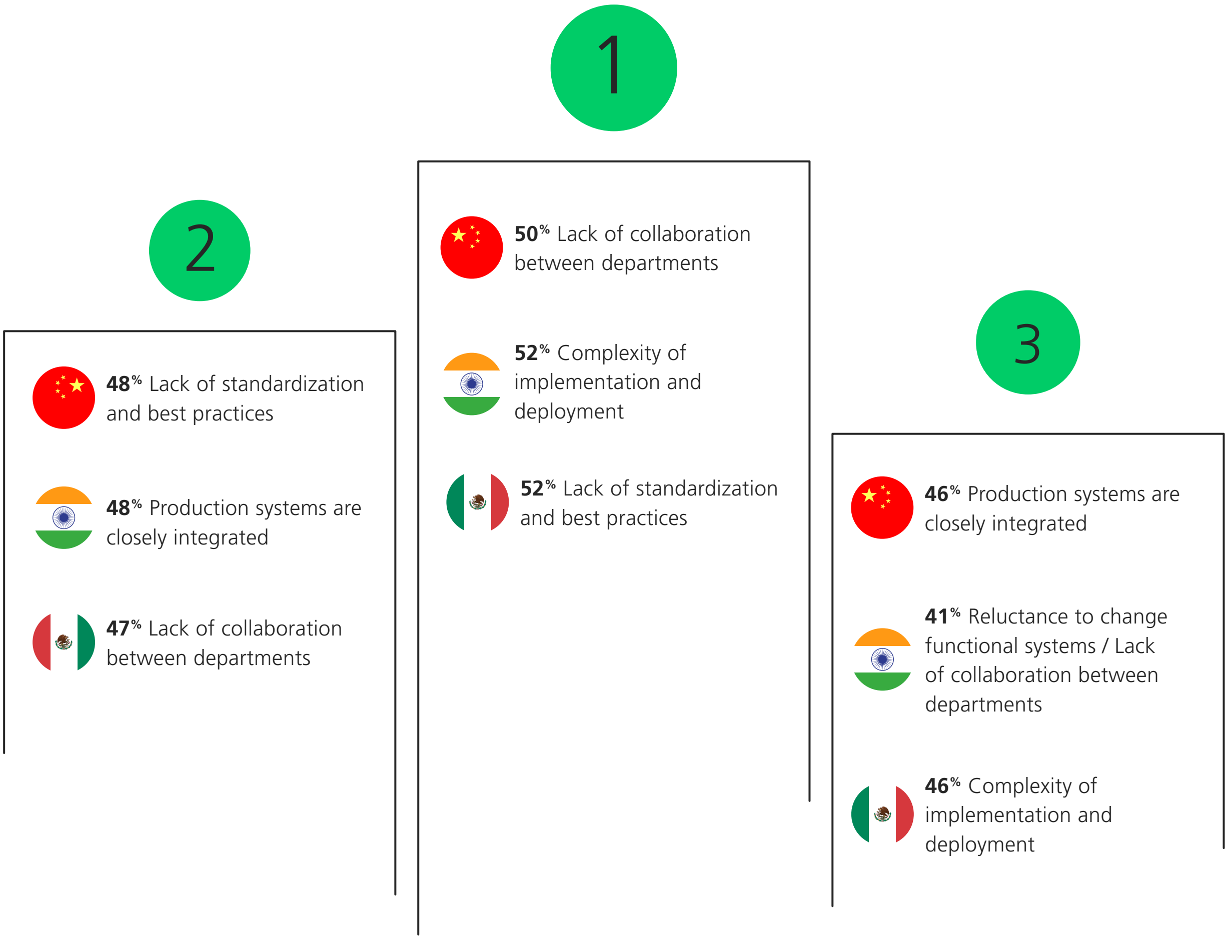


Fig. 51.2: Key operational obstacles to the adoption of modular, scalable, and flexible production systems by country (China, India, Mexico) / n – 1,206

When it comes to obstacles to advanced digital and software-controlled manufacturing solutions, the picture is even clearer (Figure 52): High implementation and conversion costs rank first among the top-3 responses in all countries (DACH 65 percent, U.S. 72 percent, UK 68 percent, China 51 percent, India 53 percent, Mexico 52 percent). In addition, operational disruption risks and organizational resistance are identified as key risks in nearly all countries. In China, an unclear or difficult-to-quantify ROI and a lower level of prioritization by top management also stand out (Figure 52).

Major obstacles
across countries

1

65% High implementation and conversion costs

68% High implementation and conversion costs

72% High implementation and conversion costs

51% High implementation and conversion costs

53% High implementation and conversion costs

52% High implementation and conversion costs

2

43% Resistance to change at various organizational levels

50% Fear of major operational disruptions during the transition

52% Fear of major operational disruptions during the transition

40% Unclear or difficult-to-quantify ROI

46% Fear of major operational disruptions during the transition

50% Resistance to change at various organizational levels

3

39% Unclear or difficult-to-quantify ROI

44% Resistance to change at various organizational levels

43% Resistance to change at various organizational levels

39% Lack of attention from top management / Resistance to change at various organizational levels

40% Resistance to change at various organizational levels

49% Fear of major operational disruptions during the transition

Fig. 52: Major obstacles to the implementation of advanced digital and software-controlled manufacturing solutions by country / n – 1,206

The cross-country comparison shows that digital transformation faces the same fundamental challenges worldwide, but that these challenges are interpreted and prioritized differently. In Western industrialized nations, the focus is on mastering complex, historically established system landscapes and securing the financial backing for large transformation projects. Costs, implementation effort, and organizational resistance are the main factors holding back progress in this regard.

In China, India, and Mexico, on the other hand, the focus is more on structural and organizational aspects. Closely integrated production systems, fragmented responsibilities, and a lack of standardization make it difficult to adopt modular approaches in these countries. At the same time, the results show that, in these regions, greater strategic clarity and management focus can determine the success of digital initiatives.

Overall, it is clear that obstacles and risks are not a sign of a lack of willingness, but rather an indication of the depth of the desired transformation. The more companies view digitalization as a transformation of their production architecture, the more cost, risk, and organizational issues come to the fore. Digital transformation will be successful where companies manage not to ignore these risks, but rather to systematically address them and actively manage them.

2.2.17 Business value

Although the adoption of digital and Software-Defined Manufacturing solutions comes with challenges, it is precisely these transformation steps that open up significant opportunities. A look at the business value reveals that the expected benefits clearly outweigh the perceived risks.

In line with this, participants were asked to what extent they considered the adoption of such advanced manufacturing solutions to be strategically relevant. 60 percent view them as a central component of their corporate strategy, 70 percent consider them crucial for ensuring long-term competitiveness, and 72 percent believe that they can significantly improve their company's market position (Figure 53).

Therefore, respondents were also asked about the specific impacts of fully implemented, digital, and software-controlled manufacturing solutions, particularly on profitability and sales. The results paint a clear picture: 84 percent of respondents expect profitability to increase, while only 5 percent fear a decrease. Regarding revenue, 76 percent expect an increase, while only 5 percent expect a decrease (Figure 54). The high level of agreement regarding positive effects can be explained primarily by the expected efficiency gains, lower setup and operating costs, and greater flexibility. As a result, companies are more likely to be able to respond more quickly to market demands, manage a wide range of product variants, and, at the same time, reduce scrap and downtime.

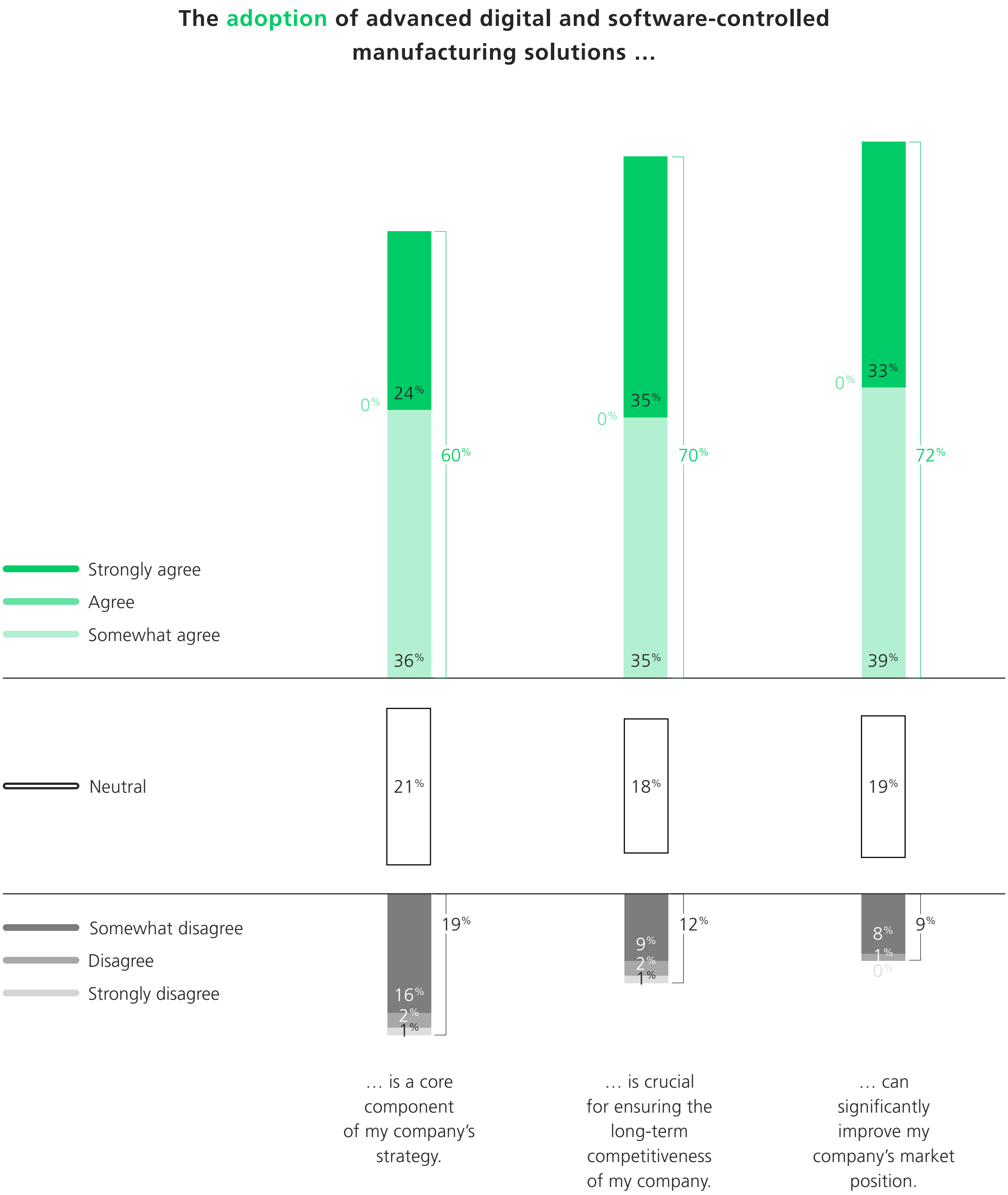


Fig. 53: Business benefits from the adoption of digital and software-controlled manufacturing solutions / n – 1,206

Imagine your company fully implementing advanced digital and software-driven manufacturing solutions. What impact would this have on …

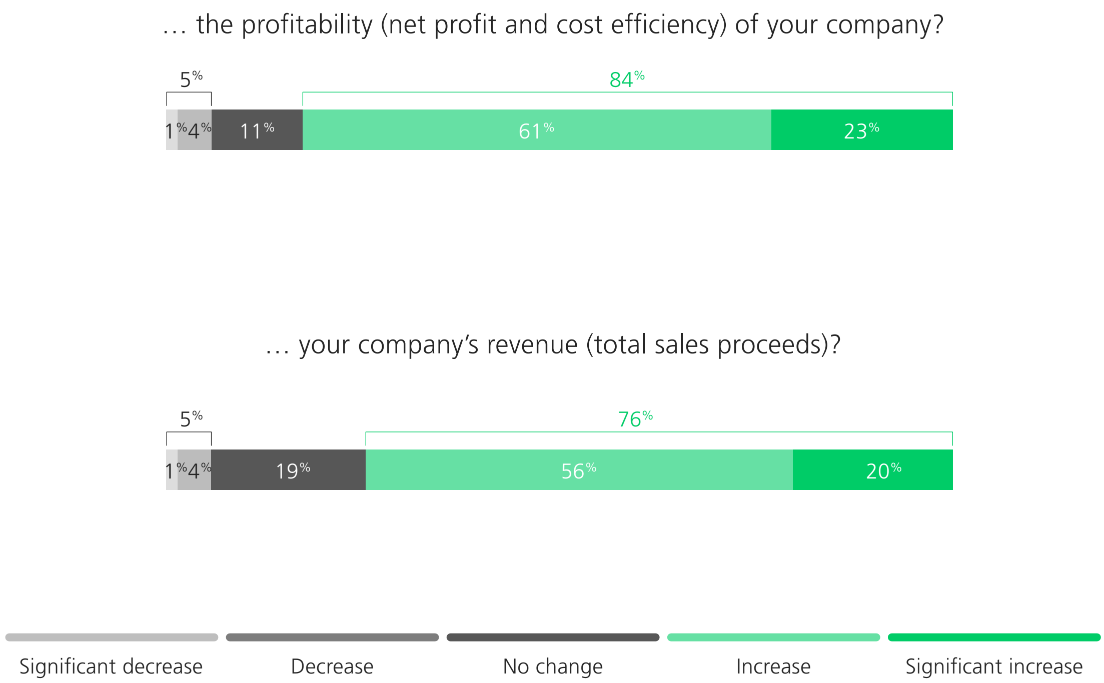


Fig. 54: Financial impact of software-driven manufacturing solutions in the company / n – 1,206

The study clearly shows that respondents see the greatest business benefits of modular, scalable, and flexible production systems in automation to minimize manual intervention and optimize processes (50 percent), improved quality control and error reduction (45 percent), and seamless connectivity between the supply chain, production, and logistics (44 percent) (Figure 55). The high priority placed on automation demonstrates the industry's clear focus on increasing efficiency through software-based control and reducing manual effort. Improved quality control is seen as an important lever for cost reduction, as real-time monitoring and error prevention directly impact productivity and scrap rates. The emphasis on connectivity between the supply chain, production, and logistics also underscores the growing need for end-to-end data integration.

What are the most impactful operational benefits of a modular, scalable, and flexible production system?

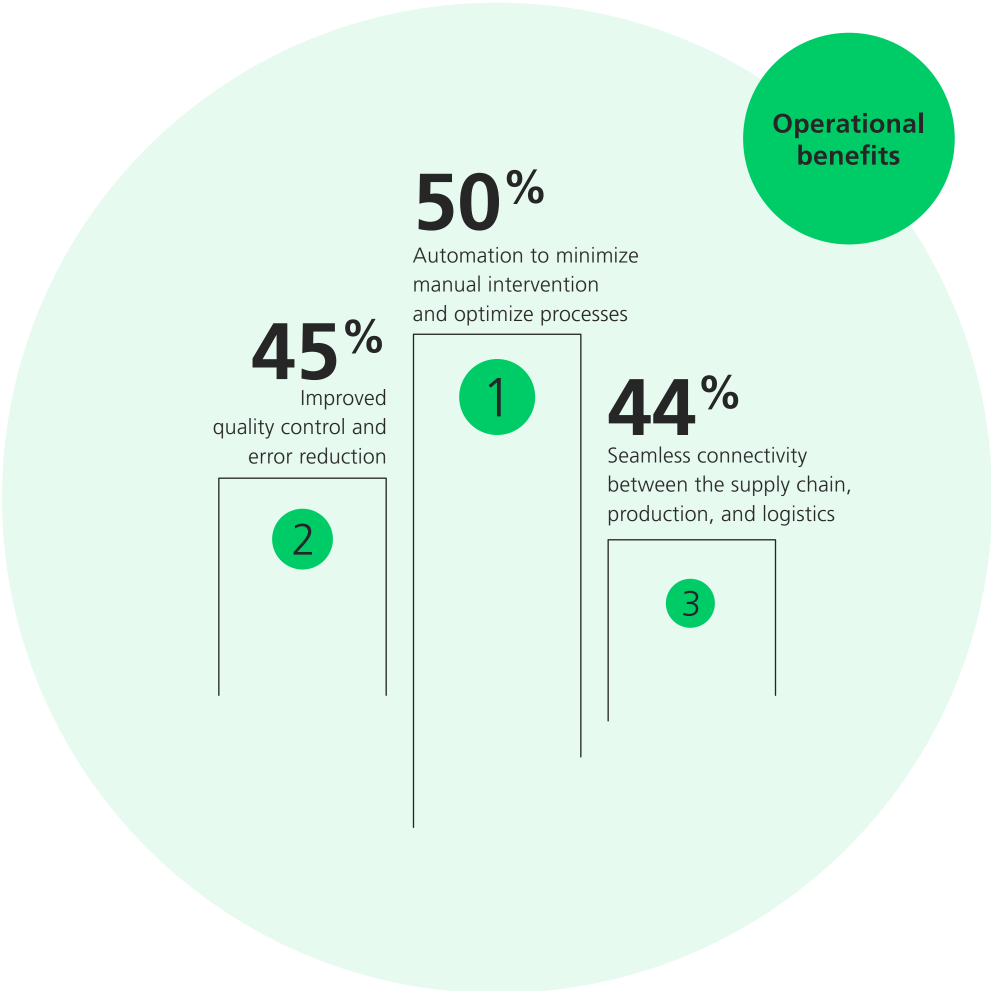


Fig. 55: Operational benefits of modular, scalable, and flexible production systems / n – 1,206

The operational advantages of modular and flexible production systems are therefore clearly evident. However, the question arises as to the extent to which companies are willing to finance these digital technologies. Apparently, the willingness is quite high: 53 percent of respondents are planning significant investments, or even major investments, in new digital technologies. Another 37 percent plan to make moderate investments, while only 10 percent intend to make minimal or no investments (Figure 56). This result confirms that companies are aware of the need for an active digital transformation. They recognize that targeted investments are the key lever for driving the transformation of their production systems.

To what extent is your company willing to invest in new digital technologies to improve production systems?

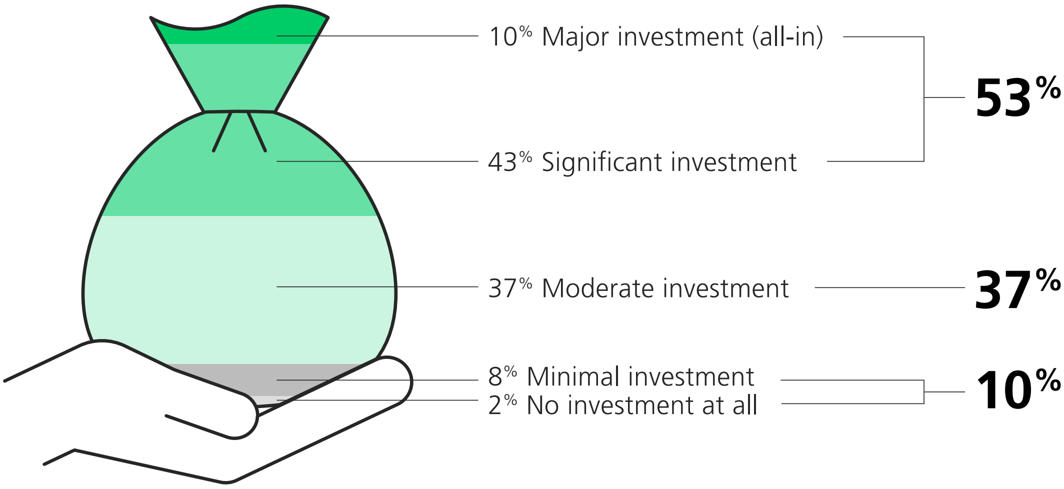


Fig. 56: Willingness to invest in digital technologies / n – 1,206

However, the country comparison makes it clear that it is mainly respondents from India and Mexico who are aware that willingness to invest is the main driver of digitalization. These regions are making significantly faster progress because they are investing more heavily and more decisively in digital production systems. Here, 71 percent of respondents from India indicate that their company is willing to make significant or large investments in new digital technologies. They are followed by Mexico at 65 percent, the U.S. at 59 percent, and China at 55 percent.

The results in the United Kingdom and the DACH region are particularly alarming. Here, the willingness to invest in digital technologies stands at 36 percent and just 29 percent, respectively (Figure 57). However, without a bolder willingness to invest, the gap threatens to widen further, which will have an impact on competitiveness, innovation capacity, and the attractiveness of these regions as business locations. The reasons for this could range from a shortage of digitally skilled professionals to short-term cost targets that lead to the postponement of investments. Therefore, a rethink is necessary. Investments in digitalization are essential in order to remain competitive in the long term and to avoid having to bear higher costs for retrofitting at a later stage.

To what extent is your company willing to invest in new digital technologies to improve production systems? Country comparison

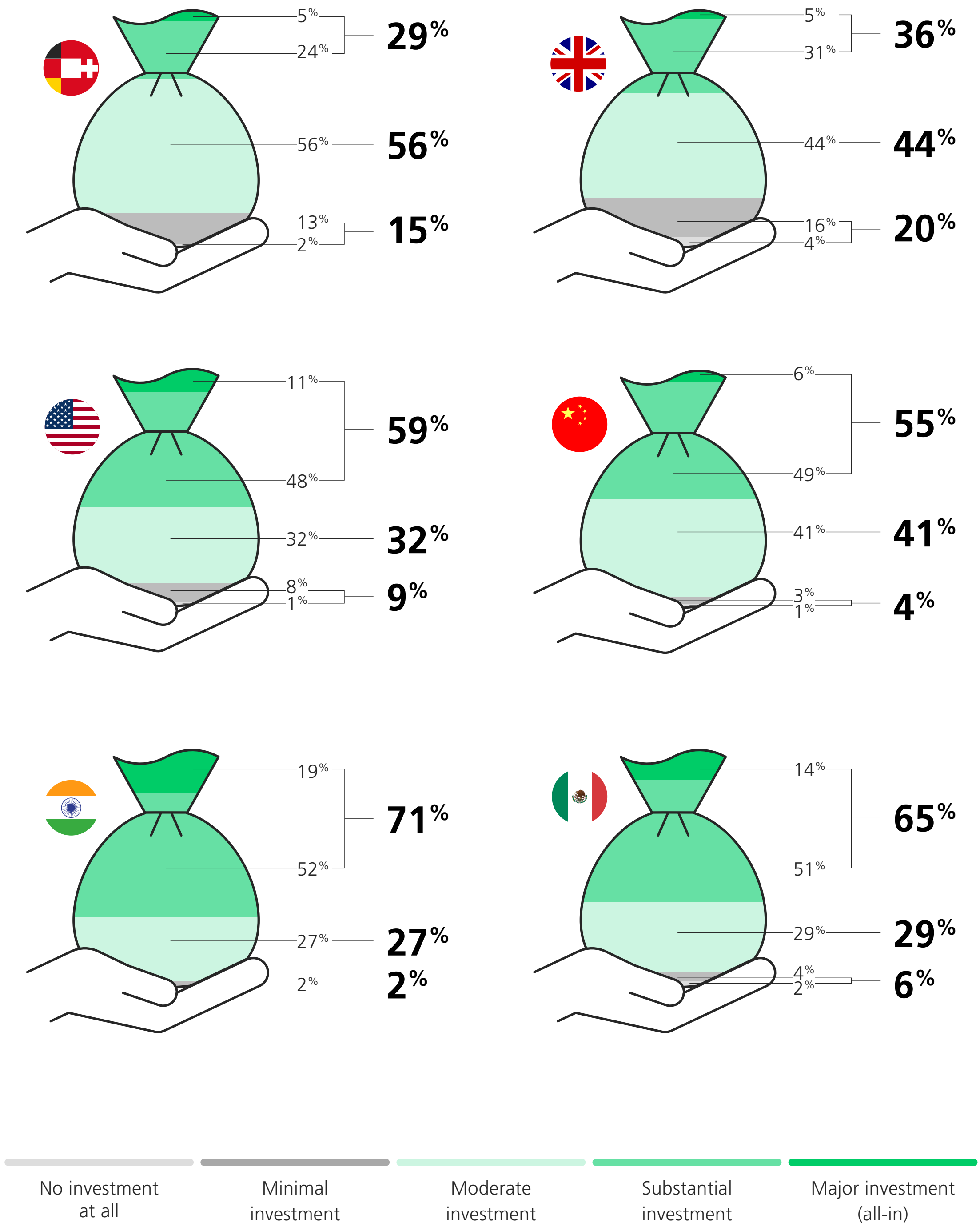


Fig. 57: Willingness to invest in digital technologies by country / n – 1,206

The high effort required for maintaining and retrofitting existing systems ties up resources that would otherwise be needed for innovation. The survey shows that technical debt, i.e., expenditures for maintaining outdated IT or production systems, has a significant impact on investments in new digital and software-controlled manufacturing solutions. Overall, 33 percent of respondents indicate that the burden of technical debt severely limits their ability to invest. A further 42 percent perceive the constraint as moderate, while only 25 percent are hardly affected by it (Figure 58). The results show that, for the majority, technical debt is a significant barrier that can delay or constrain strategic investments in advanced manufacturing technologies.

To what extent do expenditures to maintain existing technical debt (e.g., outdated IT or production systems) limit your ability to invest in new digital and software-controlled manufacturing solutions?

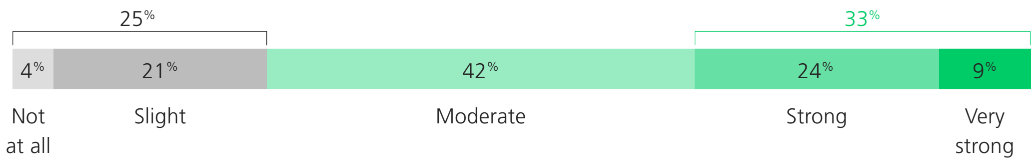


Fig. 58: Impact of technical debt on investment ability / n – 1,206

Software-Defined Manufacturing offers companies clear business benefits. Modular, scalable and flexible production systems can be used to minimize manual intervention, optimize processes and improve quality. At the same time, seamless connectivity between the supply chain, production, and logistics enables more efficient management and rapid adaptation to market demands. Companies that consistently pursue this approach while also reducing their technical debt secure lasting competitive advantages, accelerate innovation, and lay the foundation for a future-proof, digitalized production strategy.

2.3. Role of the CIO in implementing Software-Defined Manufacturing

The results of this year's Industry 4.0 Barometer make it clear that the role of the Chief Information Officer (CIO) is becoming a key driver of industrial transformation. 73 percent of the companies surveyed report that the CIO is a member of the executive management team. An international comparison reveals an even stronger integration: In China, the CIO sits on the board of directors in 90 percent of companies, followed by India at 87 percent (Figure 59). This high level of formal visibility of the CIO at the C-level is closely correlated with structural, technological, and cultural patterns of progress within companies.

2.3.1 From IT function to strategic leadership role

The data reveal a consistent pattern: When the CIO sits on the executive board, the governance logic changes fundamentally. Leadership responsibility is shifting from a traditionally CEO-centric decision-making structure to a more technology-savvy C-suite.

73%

In 73 percent of cases, the CIO/Head of IT is a member of the executive management team or the board of directors.

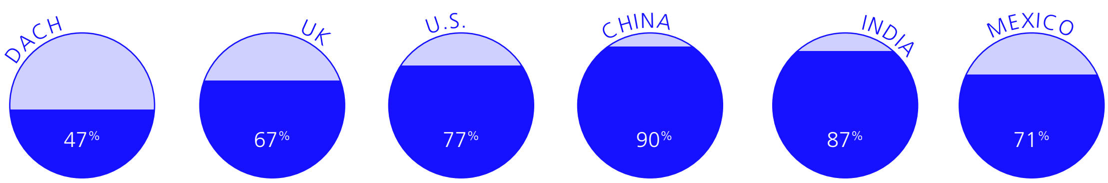


Fig. 59: The CIO in corporate governance: current status among respondents / n – 1,206

In your company, who bears the overall responsibility for digital transformation?

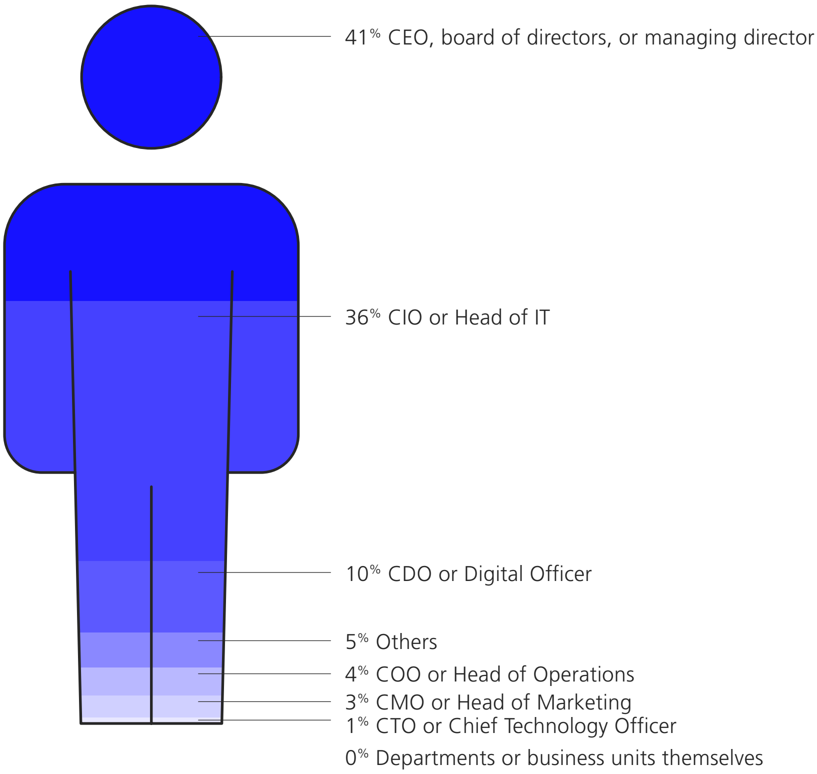


Fig. 60: Overall responsibility within the company for digital transformation / n – 1,206

Despite the CEO's continued dominant role in digital transformation (41 percent), the CIO is now represented on the board in 36 percent of companies and is most often identified as the central authority with responsibility – well ahead of the Chief Digital Officer, who, although present in 71 percent of companies, holds overall responsibility in only 10 percent (Figure 60).

This discrepancy shows that, although new roles are being created, their structural impact remains limited. The CIO, on the other hand, is involved in decision-making and investment processes and can fulfill their role both operationally and strategically. As a result, CEO dominance is declining in favor of distributed, technology-focused leadership.

2.3.2 CIO-led organizations are systematically more advanced in Software-Defined Manufacturing

The quantitative analysis shows that companies with a CIO in top management are not only more likely to be aware of Software-Defined Manufacturing (+33.2 percent), but also significantly more likely to express the intention to integrate Software-Defined Manufacturing into their overall strategy (+18.4 percent). Their willingness to make significant investments is also increasing (+13.8 percent). The CIO's influence is particularly evident in budgeting logic: Companies with a CIO shift their capital expenditure budgets 26.2 percent more in favor of new technologies, while the proportion allocated to maintenance expenses decreases (Figure 61). Thus, CIO-led organizations are addressing one of the key bottlenecks in Western industries, where, on average, 16.8 percent more of the budget is allocated to maintenance than to innovation. Here, the CIO acts as an accelerator to reduce technical debt and free up funds for future investments.

These advances have a direct impact on production:

- Manual effort is reduced by 21.9 percent,
- obstacles caused by legacy systems are significantly reduced,
- the integration of external partners becomes more stable and faster.

2.3.3 Technological maturity: A CIO completes the digital architecture

There is also a clear gap in terms of technology. Companies with a CIO on the executive team have a maturity level that is 22.5 percent higher. Their IT readiness is rated 11.5 percent higher, and their capabilities in data integration and scalability are rated around 13 percent higher in the survey. These advances have a direct impact on production, reducing manual effort by 21.9 percent, significantly lowering obstacles caused by legacy systems, and enabling faster, more stable integration with external partners.

Overall, this technological coherence results in a 13.5 percent increase in competitiveness.

The comprehensive survey results reveal the following:

- Around 50 percent of employees feel confident using software-based production systems,
- 49 percent believe they have sufficient skills to implement digital solutions,
- at the same time, 24 percent express uncertainty or significant skills deficits.

2.3.4 People & Culture: The CIO acts as a catalyst for organizational learning capability

The impact is particularly strong from the perspective of skills and culture. Companies with a CIO report that their employees have around 20 percent higher digital skills and that they have 10.3 percent better access to tech specialists in the recruitment process. The survey results show that respondents from companies led by a CIO feel significantly more confident in using production systems (+21.4 percent) compared to companies without a CIO. A clear competence advantage is also evident: Compared to companies without a CIO, respondents from CIO-led companies are significantly more likely to have sufficient competence to implement digital solutions (+19.9 percent).

This ambivalence is characteristic of industrial transformation processes: openness and uncertainty coexist. Companies with a CIO exhibit a clearer competency profile because the CIO approaches skills development, technology architecture, and organizational design in a more integrated manner. This creates a self-reinforcing cycle of greater technology expertise, an attractive talent profile, and enhanced transformational capacity.

Fig. 61: Influence of the CIO on Software-Defined Manufacturing / n – 1,206

2.3.5 Embedded in the leadership structure: The CIO is part of a trio

When it comes to the question of who plays a key role in the digitalization of production, particularly with regard to the implementation of a modular, scalable, and flexible production system, a clear picture emerges: The CTO, the Production Manager and the CIO form the dominant leadership axis (Figure 62). Therefore, digitalization is not an IT or production project, but rather a structurally integrated leadership model. The CIO combines architectural and data-driven decision-making logics and acts as the link between strategic vision, operational implementation, and technological infrastructure.

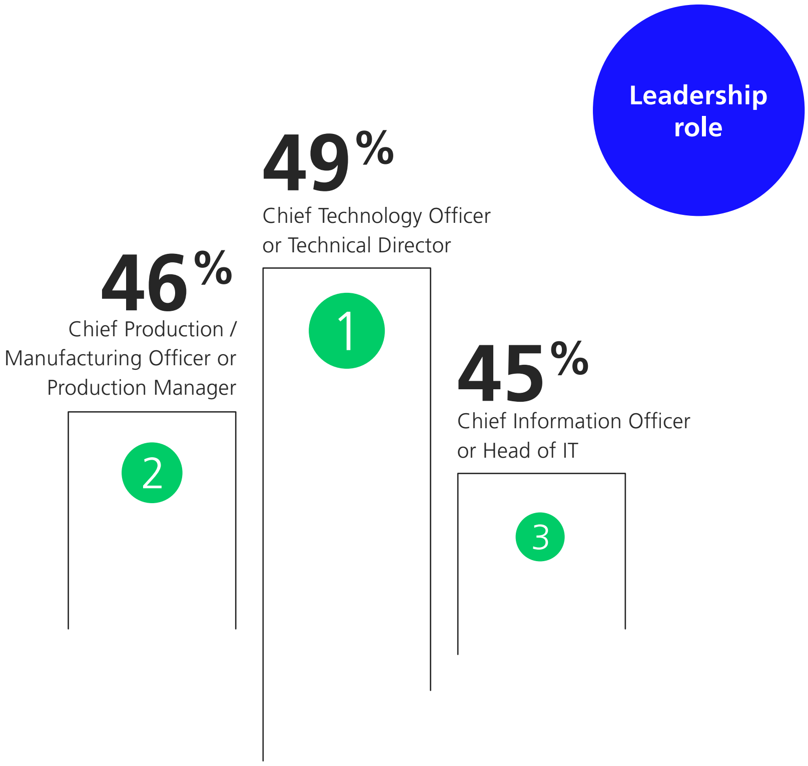
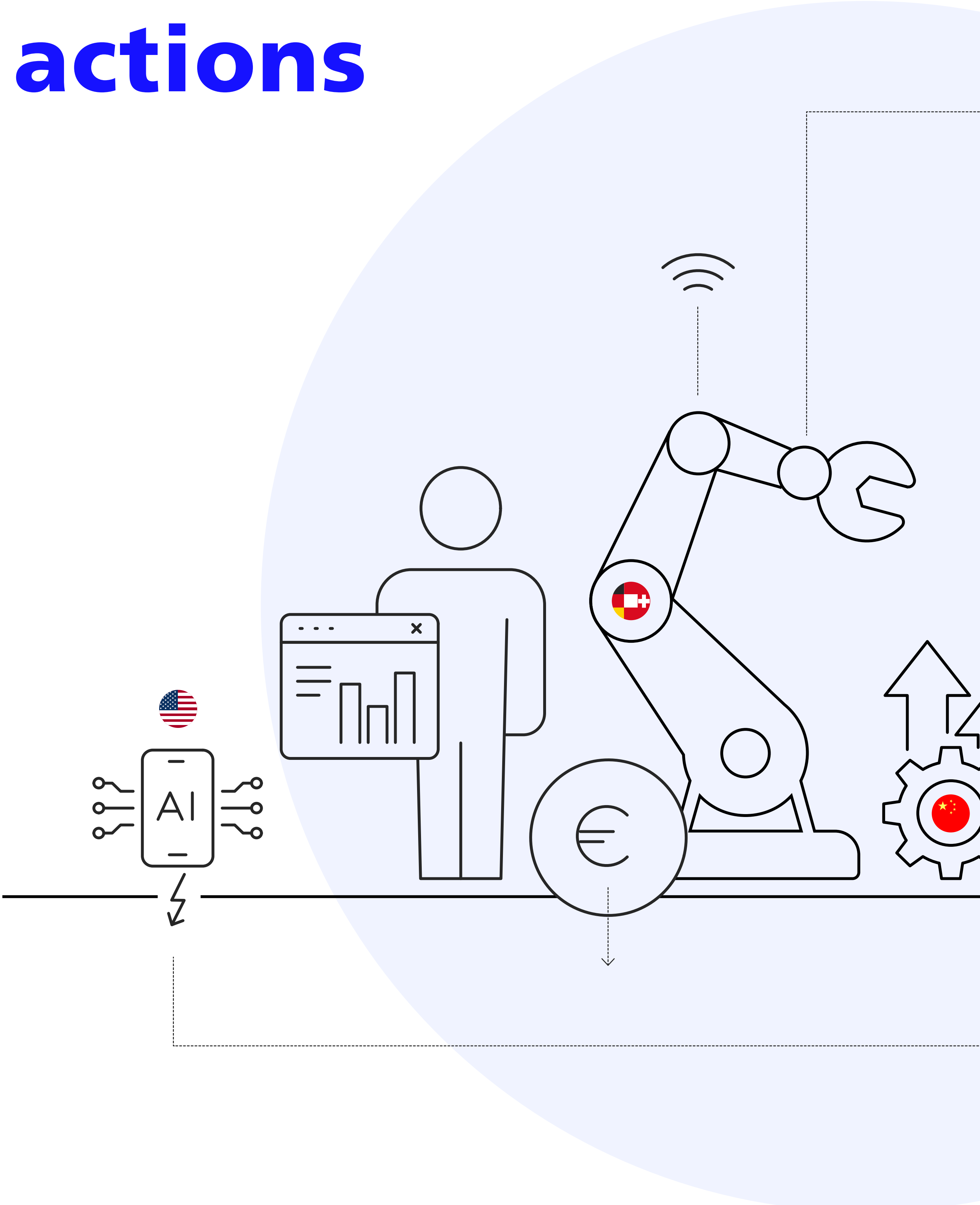


Fig. 62: Key role in implementing production digitalization / n – 1,206

2.3.6 Synthesis: The CIO as the enabler of a software-defined future for manufacturing

The overall analysis shows that, with a CIO in top management, a chain of impact is established that extends from strategic alignment and investment decisions to technological maturity and cultural empowerment. Without a CIO, Software-Defined Manufacturing often remains limited to isolated pilot projects. With a CIO in place, the likelihood that software-defined production models will become an integral part of the business model increases significantly – supported by strategic clarity, robust architectures, highly qualified employees, and targeted investment strategies. Thus, the CIO not only has an organizational role profile, but also decides whether Software-Defined Manufacturing will be tactically experimented with or strategically scaled up.

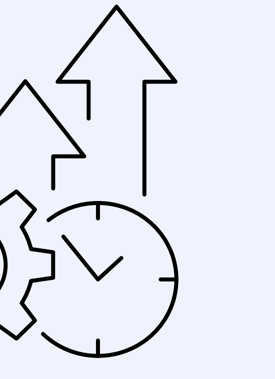
3. Conclusion and recommended actions



The international comparison reveals a consistent pattern: Asian markets – especially China – and the U.S. are implementing new digital production technologies significantly faster, more comprehensively and in a more integrated manner than European companies. A high pace of investment, modern IT/OT architectures, and the early establishment of end-to-end data infrastructures at an early stage are enabling progress in supply chain transparency, digital twins, automation, and AI-powered systems.

In Europe, particularly in the DACH region, technological progress is being held back less by a lack of potential than by accumulated technical debt. Heterogeneous legacy systems, fragmented data landscapes, limited interoperability, and infrastructural constraints – for example, in terms of network quality and IT/OT integration – make it difficult to consistently adopt new technologies. In addition, European companies are facing increasing regulatory requirements, such as the Digital Product Passport planned for 2027, which requires end-to-end data collection for traceability, the circular economy, and sustainability assessments. Many companies do not yet have the necessary data foundation, which creates additional pressure to adapt.

There are also clear regional differences in the area of AI: While companies in the U.S. are particularly optimistic about the impact of AI on production and the supply chain, Chinese companies have a more realistic assessment of the added value, as AI is already more widely implemented there. In contrast, the DACH region exhibits a more cautious assessment, which highlights the discrepancy between high expectations and actual implementation – the so-called AI hype gap.



To ensure international competitiveness, companies in Europe need to promote innovation more strongly, for example through targeted investments, partnerships, and joint ventures.
At the same time, modernizing and standardizing IT/OT infrastructures is essential to effectively implement digital twins, automation, AI, and supply chain transparency.

Overall, the Technology cluster makes it clear: Europe is facing a modernization challenge rather than an innovation challenge. Only by reducing technical debt, providing targeted investment support, and consistently implementing AI can Europe keep pace with international leaders such as China and the U.S. and fully seize the opportunities offered by the digital transformation.

To keep pace with leading regions in innovation and technological progress, strategies are needed to unlock capital, resources, and organizational capabilities. This is less about radical new developments than about transforming and modernizing existing production and decision-making processes. Only through such targeted adjustments can the existing gaps between Europe and leading regions be sustainably reduced, creating the foundation for future innovation.

Strategic recommendations for action for the digital transformation of manufacturing

Establish digital transformation as an overarching structural program

The results clearly show that digital transformation in manufacturing does not work as a collection of individual technology projects. Companies should implement digitalization as a comprehensive, structural program that addresses technology, organization, and processes as a whole. A key success factor is a clear target architecture that sets priorities, reveales dependencies, and considers solution scalability from the outset. Only when digital initiatives are consistently embedded within an overarching transformation vision can complexity be managed and lasting impact be achieved.

Reduce complexity and strategically advance standardization

A key obstacle to transformation lies in historically evolved, highly complex system landscapes. Companies should make the active reduction of technical and organizational complexity a strategic management objective. This includes harmonizing data and interface standards, reducing redundant systems, and adopting clear architectural principles. In this context, standardization is not an end in itself, but rather a prerequisite for scalability, cost-effectiveness, and speed in the implementation of digital production solutions.

Securing the economic viability of transformation and actively managing change

High investment costs, uncertainty about economic benefits, and the risk of operational disruption are holding back many digitalization initiatives. Successful companies address these risks through transparent business cases, realistic migration paths, and the definition of specific business objectives. At the same time, change management is not a secondary issue, but an integral part of the transformation. To ensure buy-in and speed of implementation, leaders must actively communicate the change, engage employees, and address organizational resistance early on.

Specific recommendations for Software-Defined Manufacturing

Establish SDM as a guiding architectural principle

Software-Defined Manufacturing should not be viewed as a stand-alone technology, but rather as a fundamental architectural principle. Strategic added value is created when control logics are consistently transferred to software and decoupled from hardware. Companies that establish IT/OT integration, modular software layers, and clearly defined interfaces as the foundation create the prerequisites for flexible, scalable, and future-proof production systems.

Implement SDM in a structured and incremental manner: **Brownfield approach**

For companies with established production landscapes – typically larger organizations with heterogeneous MES/PNC or IT/OT systems, historically developed interfaces, and complex integration dependencies – an incremental (build-up) brownfield approach is recommended. In this case, the adoption of Software-Defined Manufacturing should not require a comprehensive systems overhaul, but rather a gradual transformation based on clearly defined use cases and architectural building blocks.

A systematic approach that equally takes into account technical, organizational, and economic aspects is key. Based on a structured assessment of the maturity level of each SDM component, dependencies can be made transparent, and prioritized migration paths can be defined. New SDM functionalities are purposefully integrated into existing landscapes and scaled up gradually. This prevents a sharp increase in complexity, integration effort, and operational risks. The incremental approach makes it possible to realize benefits at an early stage and to manage risks in a controlled manner.

To this end, the MHP SDM checklist provides an appropriate methodological framework for assessing maturity levels and identifying specific areas for action.

Implement SDM in a structured and phased manner: **Greenfield approach**

In greenfield scenarios – for example, when setting up new plants, new production lines, or in smaller organizations with limited human resources and little in-house expertise – there is an opportunity to design Software-Defined Manufacturing in a consistent and coherent manner from the outset. In these cases, modular, software-based architectures can be designed without the constraints of historically evolved system landscapes.

In a greenfield context, a systematic approach is required that considers technical, organizational, and economic aspects in an integrated manner. A step-by-step approach based on clearly defined use cases remains sensible in order to keep complexity manageable and to leverage learning curves in a targeted manner. At the same time, unlike in a brownfield scenario, a more integrated approach can be taken, whereby key SDM components are introduced together at an early stage, provided that the organizational prerequisites and management capabilities are in place. Experience from large-scale greenfield implementations ("big bang" approaches) shows that it is generally possible to introduce multiple SDM components in parallel, but that this requires a high degree of governance, architectural clarity, and the ability to make changes. Here, too, a structured assessment of maturity levels, dependencies, and areas of action remains crucial in order to keep risks controllable and to ensure scalability from the outset.

Clearly establish governance and accountability for SDM

The success of Software-Defined Manufacturing depends to a large extent on clear governance. SDM requires close collaboration between technology, production, and IT. Companies should define clear responsibilities that govern strategic direction, architecture decisions, and operational implementation. An integrated leadership approach that combines CIO, CTO, and production responsibilities and establishes SDM as a shared strategic goal is particularly effective.

Figures

About MHP

MHP Management- und IT-Beratung GmbH

As a technology and business partner, MHP has been digitizing the processes and products of its around 300 mobility and manufacturing sector customers worldwide for 29 years and providing support for their IT transformations along the entire value chain. For the management and IT consultancy, one thing is certain: Digitalization is one of the biggest levers on the path to a better tomorrow. This is why the company of Porsche AG provides both operational and strategic consulting in areas such as customer experience and workforce transformation, supply chain and cloud solutions, platforms and ecosystems, big data and AI, as well as Industry 4.0 and intelligent products. Headquartered in Germany, the consultancy operates internationally with subsidiaries in the U.S., Mexico, India, the UK, Romania and China. Around 4,800 MHP employees are united by their pursuit of excellence and sustainable success. It is this aspiration that will continue to drive MHP – today and in the future.

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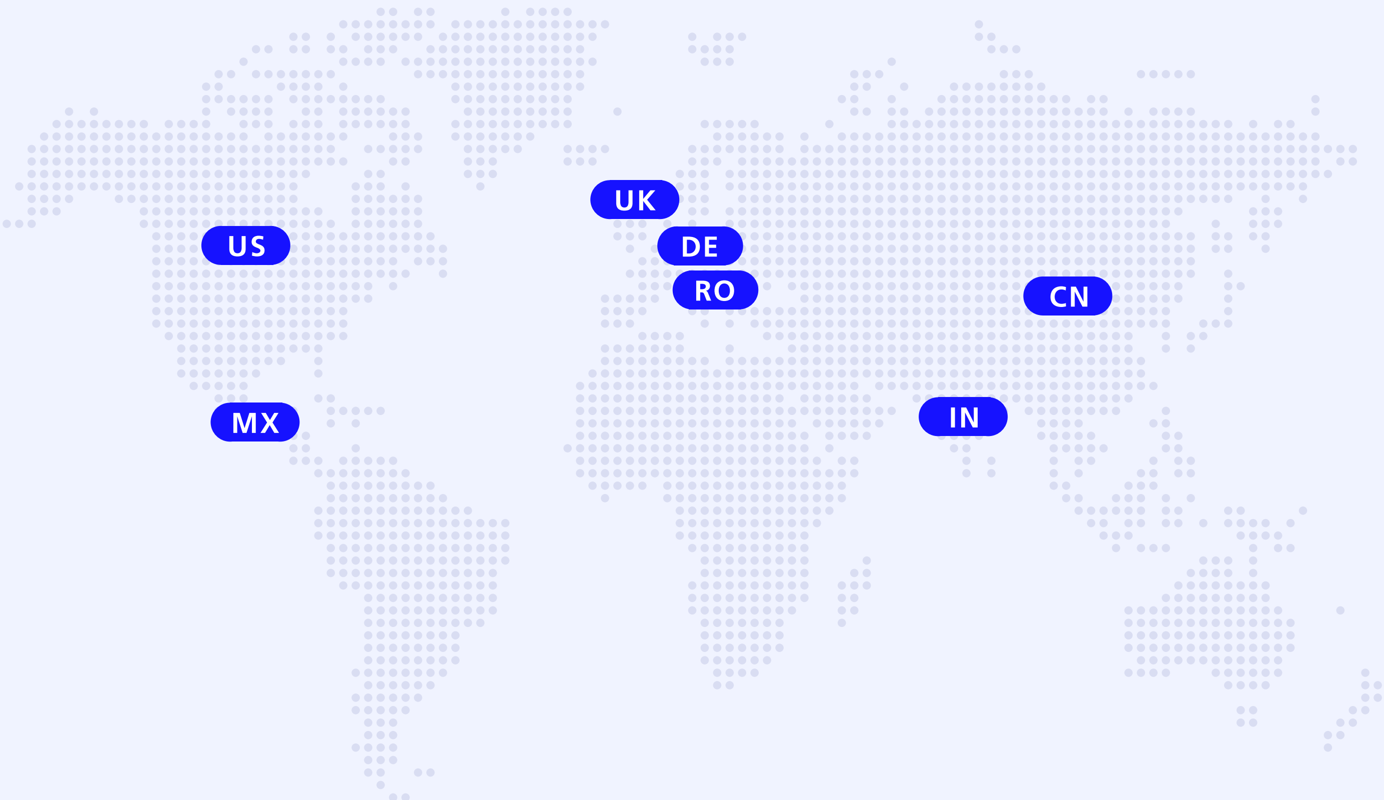

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