12.2019

Focus

Roland Berger

Rise of the machines – How robots and artificial intelligence are shaping the future of autonomous production

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Rise of the machines / *How robots and artificial intelligence are shaping the future of autonomous production*

Manufacturing industries are already using automation technologies and artificial intelligence to automate production. The shift is driven by increasing labor costs and falling robot prices: the worldwide market for robots is growing at more than 10% per year.

Fully autonomous, lights-out factories operated without the intervention of humans promise to take automation to a new level. But there are significant challenges to realizing such facilities.

To facilitate a better understanding of the concept of autonomous production and the challenges it poses, Roland Berger developed the Manufacturing Autonomy Levels (MAL) matrix. It classifies the level of autonomy in factories along two key dimensions: degree of automation and degree of control intelligence. Each is measured on a scale of 0 to 5, where 5 is full autonomy.

Only the most advanced industries (semiconductor, automotive and electronics) currently surpass level 3 in either dimension. Key barriers to automation level 4 include the lack of mobile automation and human-robot collaboration. Key barriers to control intelligence level 4 include poor access to data and a shortage of AI competencies.

Improved mobile robots and better object recognition will, for example, help companies reach higher degrees of automation. Joint research between academia and commercial providers will be key to achieving full autonomy in control intelligence.

As well as technological barriers, we also identify wider implementation challenges. These include problems with legacy equipment and a lack of IT competencies. We offer simple solutions to these issues, such as creating new expert teams and roadmapping use cases.

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1 / Rise of the machines

MANUFACTURERS ARE ALREADY ON THE PATH TO A FULLY AUTONOMOUS, LIGHTS-OUT FACTORY

The ever-increasing power and precision of automation technologies and artificial intelligence (AI) are changing the way whole industries operate. Across the spectrum, these advancements are increasing efficiencies, enabling cost savings and disrupting whole business models. Few stand to benefit more than manufacturing industries, with their vision of the so-called lights-out factory. In it, human operators are no longer required, with robots instead producing, packing or sorting products on their own.

The shift is already underway. Robot types and capabilities have increased significantly over the past three decades, with, for example, payloads increasing by 2,000% to 2,300 kg today. In addition, the machines have been equipped with sensors that work in a similar way to human sense organs, allowing them to see, hear and even walk. But is the dream of a lights-out factory, handling even low volumes, realistic? And if so, when will it be realized?

There are several positive indicators, mostly linked to cost consciousness – the key driver for operational performance across the manufacturing industry. While labor costs in Germany, for example, jumped by around 25% in the past ten years, the price of industrial robots fell by around 30%. The automotive and electronics industries alone are buying more than 120,000 robots every year, with the worldwide market for industrial robots growing at more than 10% every year. Our project experience suggests that once most companies introduce industrial robots it will result in a 15% to 25% fall in direct labor costs in high-wage countries, and a 5% to 15% fall in low-wage countries.

This reflects the fact that, for the time being at least, manufacturing plants still require human interactions, for example to maintain robots. But lights-out factories, using features such as new AI-based control tools that can manage almost all predictable events, will take automation to a new level. They offer better cost-benefit, improved output quality and reduced interdependencies in the workforce, for example when it comes to finding skilled employees or workplace injuries. Yet there are good reasons why lights-out factories have not been widely deployed. They present significant technical and implementation challenges, from mastering robot autonomy to heavy investment and factory redesigns.

The aim of this report, therefore, is to discuss industry and task-specific approaches to autonomous production, and the challenges they pose. Based on interviews with manufacturing CEOs and COOs, it offers a new way to classify the level of autonomy in production plants using a specially designed matrix, as well as solutions to implementation challenges.

"Our project experience suggests that once most companies introduce industrial robots it will result in a 15% to 25% fall in direct labor costs in high-wage countries, and a 5% to 15% fall in low-wage countries."

Dr.-Ing. Bernhard Langefeld
Partner

2 / Levels of autonomy

WHAT IS AUTONOMOUS PRODUCTION AND WHICH MANUFACTURING INDUSTRIES ARE USING IT?

To fully assess how far manufacturers are away from the lights-out factory, we first need to define the term autonomous production. As there is currently no clear definition, we developed the Roland Berger Manufacturing Autonomy Levels (MAL). → A

MAL EXPLAINED

The RB MAL matrix maps both the degree of automation and the degree of control intelligence in a factory. Scores for these two factors can then be combined to produce an overall autonomy level.

The **degree of automation** describes the capability of production equipment to perform a defined set of tasks without human intervention. Its lowest level (0) corresponds to completely manual production, and its highest (5) to fully automated production. In more detail:

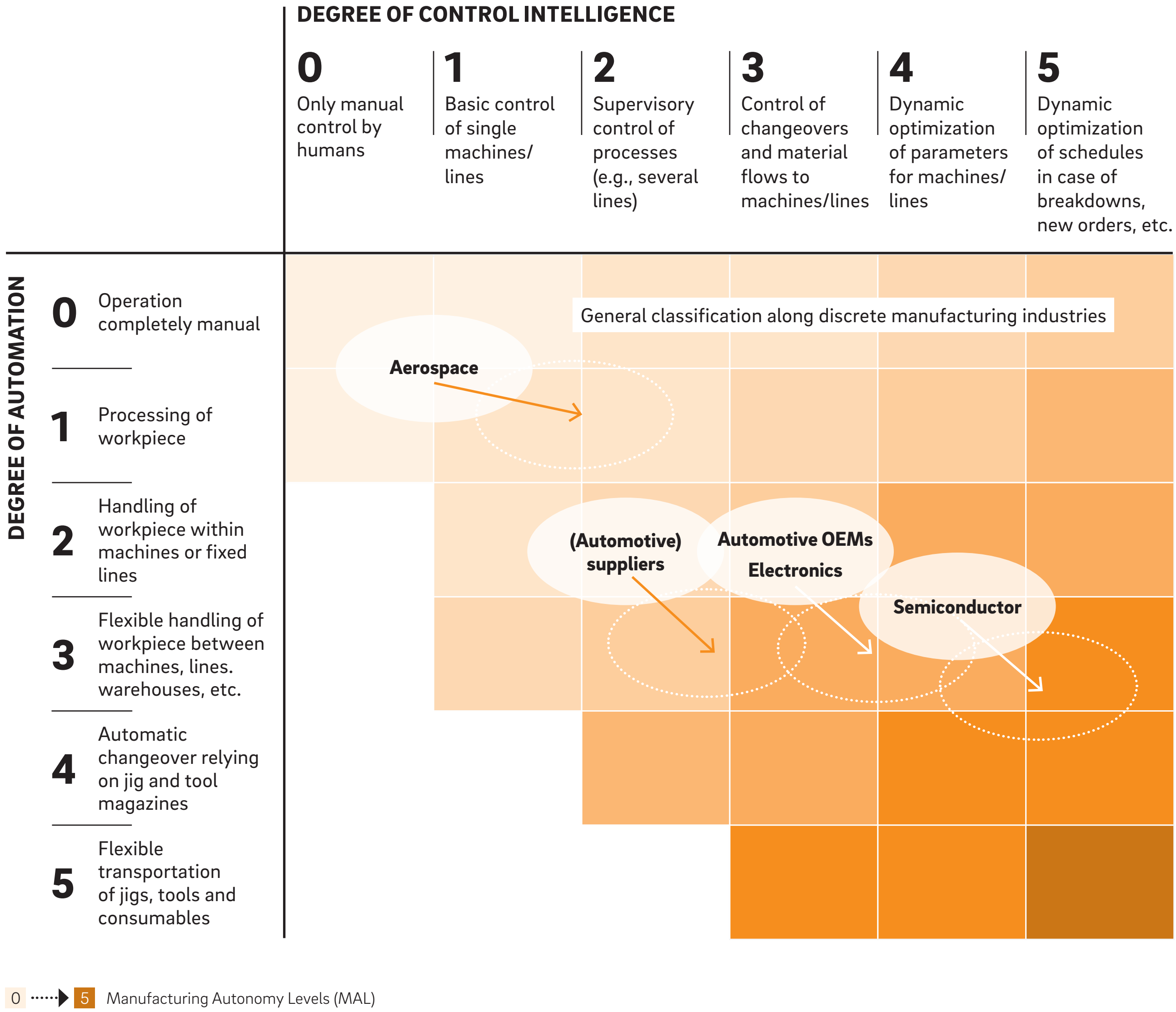
Level 0: Operations are completely manual, e.g., holes are drilled with a hand-held drilling machine.
Level 1: The processing of workpieces is automated, e.g., through a computer numerical control (CNC) processing center. However, handling is still manual.
Level 2: Structured, simple handling and transport tasks are automated in fixed processing lines.
Level 3: Complex handling and transport tasks are automated in flexible processing lines, with the ability to handle unstructured parts.
Level 4: Mobile robots perform "picking and kitting" of items as well as changeovers of tools and workpieces.
Level 5: Mobile robots autonomously perform complex production and changeover tasks. In addition, selected repair tasks are automated.

Next we consider **degree of control intelligence**. This describes the ability to automatically steer and orchestrate several production processes across multiple pieces of equipment. The lowest level (0) corresponds to a human-only control mechanism, while the highest (5) requires a dynamic, smart and self-optimizing control system:

Level 0: Workers manually control machines, e.g., by setting the motor speed of a lathe or moving a cutting tool with winches.
Level 1: Machines or simple lines are automatically controlled, e.g., by a programmable logic controller (PLC), computerized numerical control (CNC) or industrial PC (IPC).
Level 2: Processes (multiple lines) are controlled through setpoints and commands from a central controller, e.g., a distributed control system (DCS), supervised control and data acquisition system (SCADA), or SCADA function of a manufacturing execution system (MES).
Level 3: The production schedule is executed by distributing and triggering machine programs and work orders via a central system, e.g., an MES.
Level 4: Machine learning is used to optimize the control parameters of machines and lines.
Level 5: Historic/current production data is used to dynamically optimize production schedules in real time.

Overall, the higher the degree of automation and control intelligence, the higher the autonomy level rating (the diagonal scale in the matrix) in the RB MAL.

A: Manufacturing autonomy levels
The MAL matrix compares degree of automation against degree of control intelligence



Source: Roland Berger

3 / Technological barriers

THE ROBOT AND DATA CHALLENGES PUTTING THE BRAKES ON AUTONOMOUS PRODUCTION

HOW DIFFERENT INDUSTRIES PERFORM

By mapping different factories into the RB MAL, we were able to gain a clear picture of industry trends in autonomous production. While no industry has yet reached Level 5, there are clear leaders – mostly those with a short plant lifecycle and high volumes – as well as laggards.

The semiconductor industry, which has developed its own approach to transform manufacturing facilities into smart factories, has the highest maturity levels. A significant number of automotive OEMs' factories also show mature degrees of automation and control intelligence. These companies drive innovation and invest more in fully automated projects and facilities, such as Mercedes' Factory 56, its new "digital, flexible, green" production facility in Sindelfingen, Germany.

Automotive suppliers are at a similar level in terms of automation, but lag behind when it comes to control intelligence. This is mainly because of their focus on the control of individual (customer) lines, instead of the autonomous control of the whole factory.

As a result of complex structures and lower volumes, the aerospace industry is quite significantly behind. It only made its first investments in smart digital factories recently, with Turkish Aerospace Industries among the first to announce a smart factory in 2019.

The mapping of different industries on the RB MAL emphasizes the difference in autonomous production maturity levels among different industries. But what makes one worse than the other? To evaluate how industries are developing in terms of their manufacturing autonomy, it's important to understand the technological barriers facing autonomous manufacturing.

For clarity, we have split these challenges into the same two dimensions used in the RB MAL: automation and control intelligence.

BARRIERS TO AUTOMATION

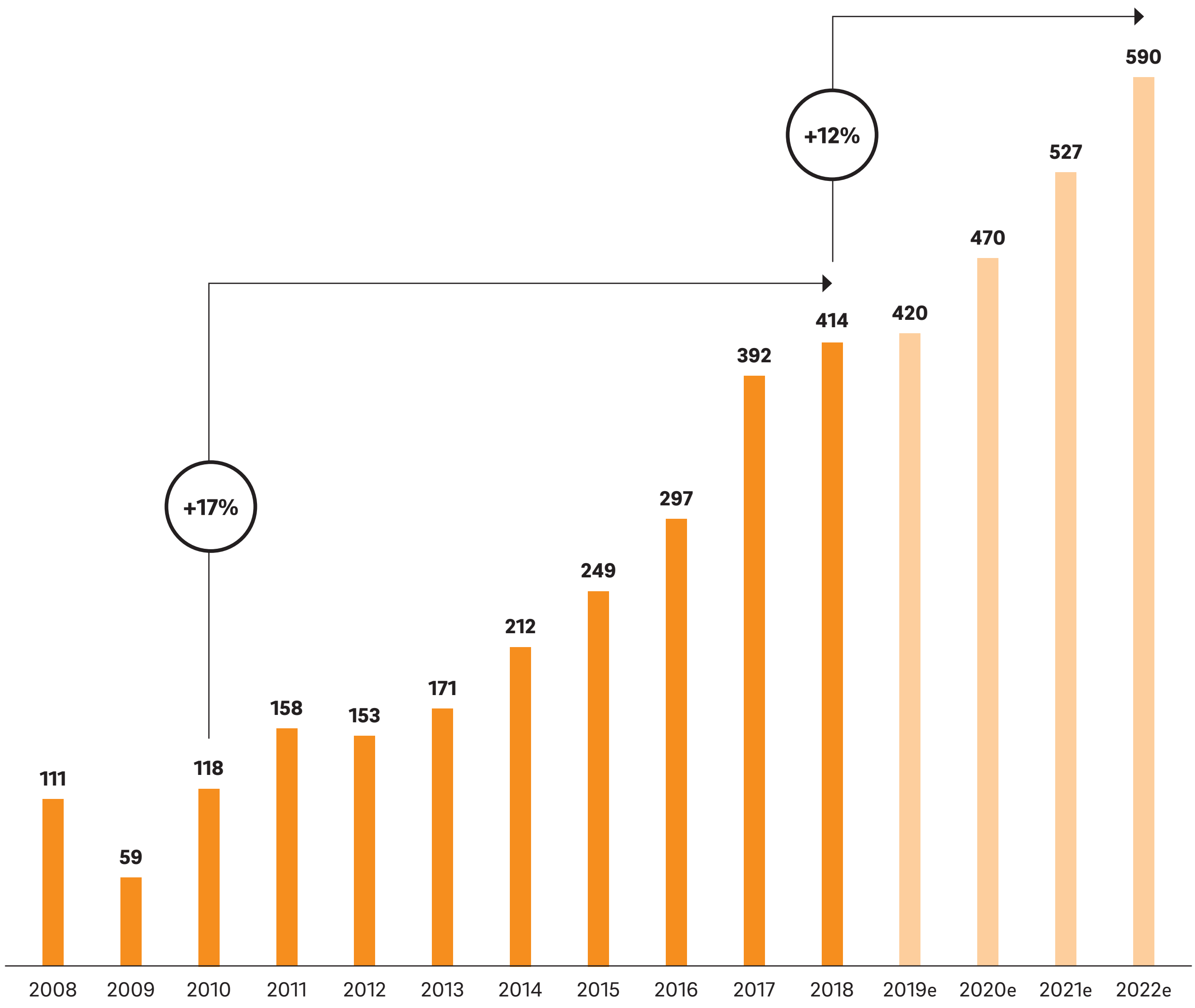
The industrial robotics industry is booming. It has seen growth of 17% in the past decade, and while the sector has stagnated recently due to the economic slowdown, growth is projected to remain in double-digit territory over the next few years. The main drivers are rising labor costs, especially in emerging economies, falling robot prices and technical improvements. → B

However, the growth is largely attributable to the scaling up of sales of conventional robot technology. These are regular industry machines, in some cases reliant on 60-year-old technology, that are limited to conducting repetitive tasks along clearly prescribed trajectories.

To bring about real step change and lift the degree of automation to the next manufacturing autonomy level, six key challenges need to be addressed. These are: picking and identification of unsorted items; safe human collaboration and economic speed; mobile automation of inspection and repair; adaptive control using machine learning and advanced sensors; mobile automation of complex production tasks; and advanced human-machine interface. We detail the barriers to progress in tabular form later on. → C

How do these challenges interact with the RB MAL matrix? Overcoming certain challenges enables

B: Robotic growth
Annual global installations of industrial robots from 2008 ['000s]



Source: IFR – World Robotics Report: Industrial Robots 2019 companies to move up the degree of automation dimension. In short, they are key enablers of autonomous production. In addition, companies will have different requirements for automation technology depending on their level of autonomy.

For example, overcoming the challenge "Adaptive control using machine learning and advanced sensors" is a key enabler to move from dealing with structured, simple tasks in fixed lines (2) to handling unstructured workpieces such as fruit in a more a flexible environment (3).

Also, the challenges of mobile automation and human collaboration with robots ("cobots") play an important role in reaching the fourth degree of automation – picking and kitting, as well as changeovers of tools and workpieces, using mobile robots. Mastering these challenges enables flexible production concepts, such as mixed lines in which cobots selectively take over assembly tasks from humans to improve line balancing.

And the robust bin picking and object recognition capabilities required to pick and identify unsorted items are a key enabler for maneuvering in unstructured environments (3).

BARRIERS TO CONTROL INTELLIGENCE

Technologies that function at the third degree of control intelligence (essentially where a central system controls the production schedule) have been available for many years, and new advancements are now enabling levels 4 and 5 of the automation pyramid. The sheer scale of the technological advancement is evidenced by the fact that the original automation pyramid only went up to level 3. Our infographic maps the technology types against their degree of control intelligence. The technologies and their area of operation are shown on the left of the pyramid, and the physical location of their supporting software at the bottom. → D

Engineers usually have to economically model optimization algorithms, but in these cases they are too complex to model. Indeed, manufacturers need large amounts of process data and data-driven artificial intelligence tools, specifically machine learning, to make sense of it.

Unfortunately, both are in short supply. For example, an automated vision-based quality inspection system is trained to spot anomalies by being shown a large number of components with errors. But even in the high-volume automotive industry, series sizes do not have enough erroneous parts to train the system, even after several months. And while cloud providers such as Microsoft and Amazon Web Services offer platforms with standard algorithms and the necessary computing power for AI, they do not have the necessary process data. So although they can provide the infrastructure, the manufacturer still has to implement the use cases.

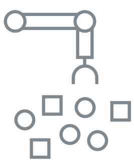
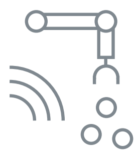
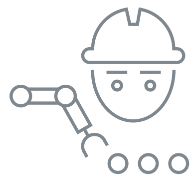
As a result, there is currently a large gap between technologically possible level 4 and 5 use cases (developed in research settings and piloted in the field), and standard solutions provided by commercial automation companies. This is highlighted by the fact that there has been significant research into dynamic scheduling optimization (semiconductor industry) and parameter optimization (injection molding).

However, we see that machine builders are increasingly focusing on solutions for the optimization of machines. They're doing this because they have access to data from all their customers' machines, rather than just the machines of one manufacturer, enabling them to build up a significant database. The German machine producer Trumpf, for example, is leveraging machine learning to enable the separation of parts after the laser cutting process.

The upshot of this is that we expect the number of standard solutions for manufacturing process optimization to increase in the near future. Interestingly, these are unlikely to come from one major player in the market – MES Provider. It currently offers solutions

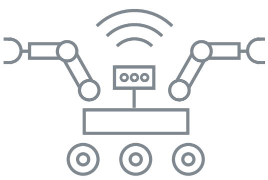
C: Barriers to progress

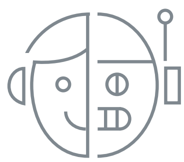
The key challenges to industrial automation, with their RB MAL profile

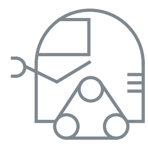
			
CHALLENGE	**Picking and identification of unsorted items**	**Adaptive control using machine learning and advanced sensors**	**Safe human collaboration at economic speed**
CURRENT STATUS	· Not yet in industrial application, only in pilot areas · Problems with changing ambient light or when parts are packaged	· Robots typically rely on a pre-described trajectory and use lasers or vision systems for position control · No force sensing yet	· Mostly used for simple tasks in close proximity to humans · Often not economical due to slow movement of robot and high investment
FUTURE OUTLOOK	· Autonomous picking and kitting of parts from bulk storage · Autonomous part recognition using vision sensors	· Real time self-adjustment using machine learning, vision and force control becomes widely adopted · Integration of multiple data sources beyond vision and force sensing	· Fast and safe robots with smart pre-collision sensing · Strong interaction with human workers, while taking over comparable tasks
USE CASES	· Seamless automation along process chains · Reduced process disturbance due to human influence	· Dealing with high workpiece variability and/or delicate tasks · Optimizing production parameters to increase product quality	· Flexible balancing of assembly lines in response to demand fluctuation · Robots taking over unergonomic, dangerous or repetitive tasks
APPLICATION EXAMPLE	**Mobile robots autonomously pick and kit parts in the warehouse**	**Polishing of a complex surface with uncertain positioning**	**Robots and humans working together on interchangeable tasks at the same workstation**
DEGREE OF AUTOMATION	5 4 3 2 1 0	5 4 3 2 1 0	5 4 3 2 1 0

Key enabler Enabler

Source: Roland Berger; Illustrations: The NounProject



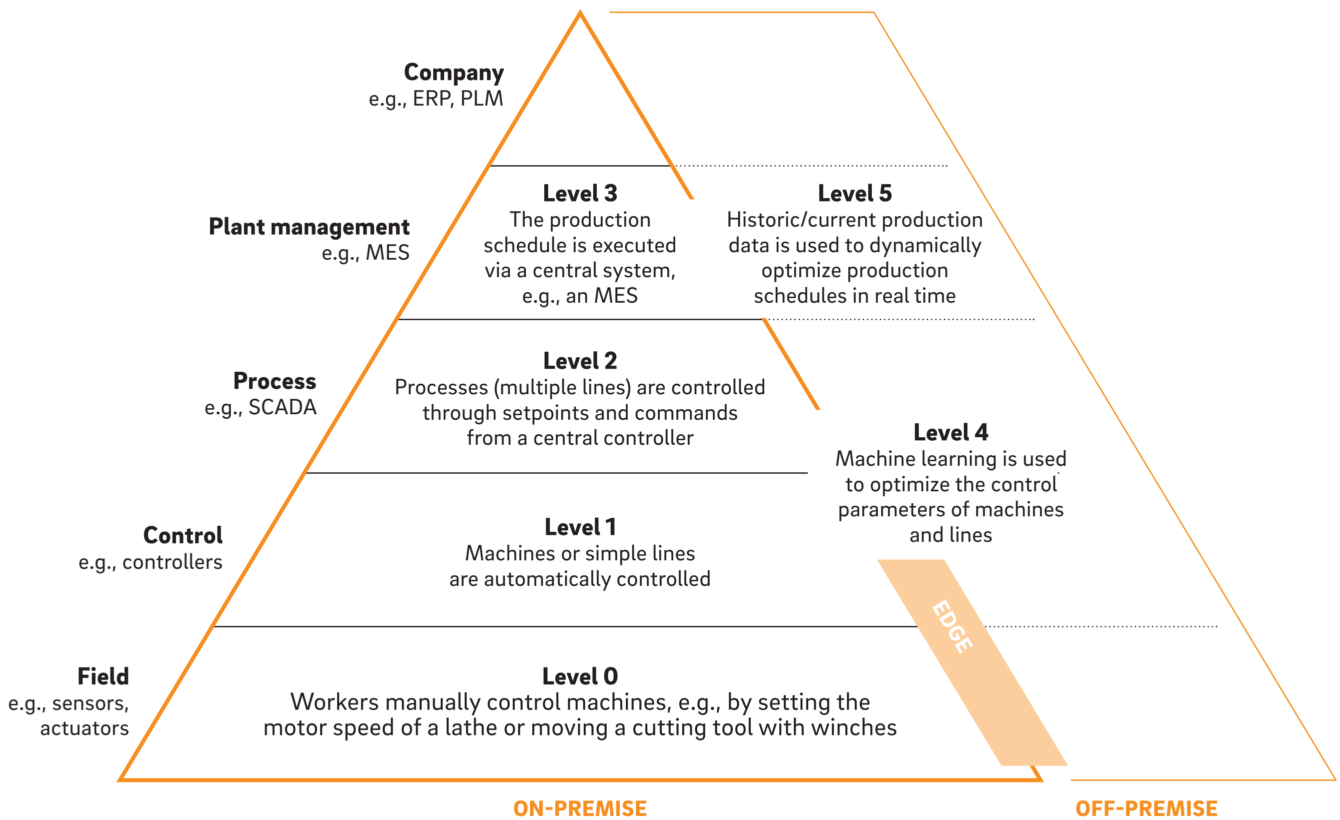




Mobile automation of complex production tasks	Advanced human machine interface	Mobile automation of inspection and repair
· Mobile automation almost exclusively used for shop floor transport (AGVs) · Mobile pick and place robots in pilot status	· Programs created by engineering department · Manual teaching, virtual reality and gesture control in pilot applications	· Autonomous mobile inspection in niche applications · Repair tasks almost exclusively performed by humans
· Autonomous mobile robots mounting parts in different locations while covering large areas · Loading and shop floor transport by the same robot	· Programs created by frontline operators · Approximate teaching of self-learning robots using gesture and voice control · Virtual reality for offsite programming of robots	· Autonomous inspection, e.g., by drones or AGVs · Big data analysis with real-time link to process data · Autonomous simple repair jobs using mobile robots
· Processing large stationary workpieces · Replacement of humans in hazardous environments like painting or grinding	· Low-volume production with frequent process adjustments · Limited programming expertise within company	· Online inspection without need for safety shutdown · Mobile use of sensors (e.g., emissions, temperature, visual nonconformities)
Mobile robots autonomously perform assembly tasks in aircraft fuselage production	**Robot engineer programs robot from offsite using virtual reality**	**Autonomous drones identify worn-out conveyor bearings using thermal imaging**
5 4 3 2 1 0	5 4 3 2 1 0	5 4 3 2 1 0

D: Automation pyramid

Control intelligence technologies by level, layer of operation and location



Source: Roland Berger

for production scheduling but has chosen not to focus on automation scheduling decisions using machine learning. This means that the development of level 5 control intelligence solutions will likely lie completely with manufacturers.

Joint projects between manufacturers, including small startups, and academia, such as universities and private institutes, will be key here. They are expected to drive the wider rollout of level 5, albeit at a much slower pace than process optimization.

Ultimately, we predict that while more and more manufacturers will adopt use cases for machine/line optimization in the near future, only a few manufacturers will reach level 5 in the same timeframe.

4 / How to implement autonomous production

THE CHALLENGES AND THE SOLUTIONS

It's clear from the preceding chapters that current technologies allow for autonomy levels of between 3 and 4 in most industries. Why, then, are many companies still operating at levels 1 and 2? Technical difficulties aside, the key reason is the myriad challenges involved in actually implementing new automation and control intelligence measures.

IMPLEMENTATION CHALLENGES

We see three main obstacles. The first is that many production sites have grown organically over time and as such now consist of a mix of modern and legacy equipment. This may mean that interfaces are missing, communications standards are incompatible and that there are many different software systems.

Second, a lack of competencies in IT and in particular AI limit manufacturers' ability to identify and implement potential use cases, and trust new technologies. Building up such competencies is difficult because there is a dearth of experts in the marketplace.

Lastly, there are no turnkey providers that can upgrade existing plants to a certain automation level. Competencies at the various technology providers need to match the manufacturer's expertise to achieve higher levels of autonomy.

"Why are many companies still operating at autonomy levels 1 and 2? Technical difficulties aside, the key reason is the myriad challenges involved in actually implementing new automation and control intelligence measures."

Dr.-Ing. Markus Moehrle
Project Manager

IMPLEMENTATION SOLUTIONS

We have developed five simple recommendations to help companies overcome the implementation challenges.

1. Identify your company's optimal level of autonomy, taking into account all existing constraints.

2. Create new teams consisting of experts from manufacturing (ensuring process experience) and IT (ensuring AI competencies), as well as the necessary organizational structure to drive the shift to higher autonomy levels.

3. Identify and prioritize in a roadmap the various technologies and use cases required to reach the desired autonomy level.

4. Identify partners from industry (suppliers) and academia, to support the implementation of the identified and prioritized use cases.

5. Implement pilot use cases in order to build up experience, knowledge and the trust of the various stakeholders in the new technologies.

Conclusion

It's clear from our research and interviews that the autonomous production revolution is well underway. But it's also clear that this transformation has hit technological and implementation barriers. If manufacturers are to overcome these and continue on the path to the lights-out factory, they must start planning and executing solutions now, before their rivals gain an edge. They must also enlist the help of expert partners to support them on the journey. Roland Berger stands ready to assist.

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We welcome your questions,
comments and suggestions

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PUBLISHER:
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RB_PUB_19_032