In collaboration with Boston Consulting Group

World Economic Forum

Transformation of Industries in the Age of AI

Frontier Technologies in Industrial Operations: The Rise of Artificial Intelligence Agents

WHITE PAPER

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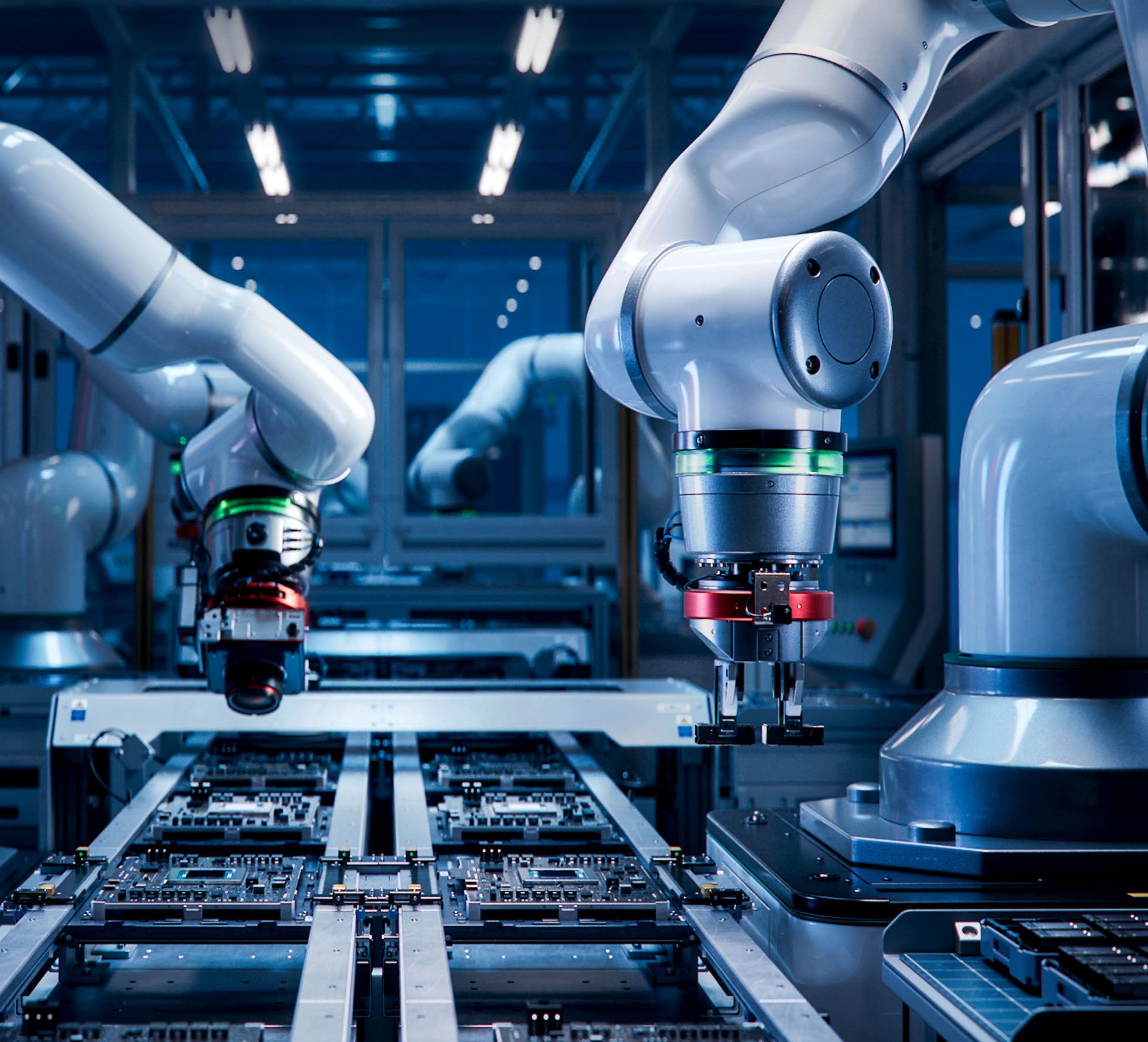

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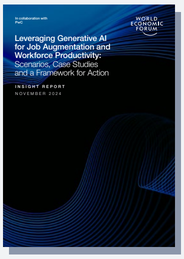

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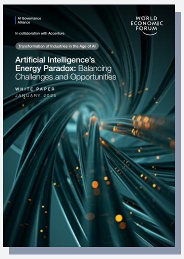

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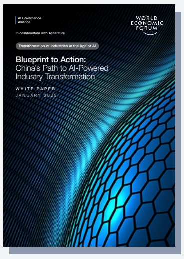

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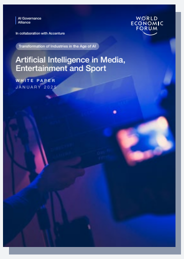

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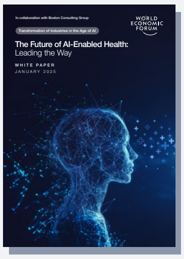

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As AI continues to evolve at an unprecedented pace, each paper in this series captures a unique perspective on AI – including a detailed snapshot of the landscape at the time of writing. Recognizing that ongoing shifts and advancements are already in motion, the aim is to continuously deepen and update the understanding of AI's implications and applications through collaboration with the community of World Economic Forum partners and stakeholders engaged in AI strategy and implementation across organizations.

Together, these papers offer a comprehensive view of AI's current development and adoption, as well as a view of its future potential impact. Each paper can be read stand-alone or alongside the others, with common themes emerging across industries.

Foreword

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Amid a landscape of exponential technological change, society is entering the Intelligent Age[1] – an era defined by far more than technology alone. The Intelligent Age is characterized by a mass revolution transforming all aspects of society, and we're already beginning to witness profound shifts. Alongside technological intelligence, environmental, social and geopolitical intelligence will be fundamental to success in this age.

In this new era, industrial operations are being redefined. To better understand emerging opportunities and explore potential responses, the World Economic Forum – in collaboration with Boston Consulting Group (BCG) – launched the global initiative Frontier Technologies for Operations: AI and Beyond. Building on the success of our previous AI-Powered Industrial Operations initiative from 2022, this new scheme aims to equip manufacturers with the insights and tools necessary to shape the future of industrial operations in the Intelligent Age.

It's important to address two pressing questions – why focus on frontier technologies, and why now? The answer is simple yet profound – these innovations, like others in the Intelligent Age, drive boundary-breaking advancements that push the limits of what's currently possible, facilitating collaborative intelligence and amplifying human ingenuity. In doing so, they provide competitive advantages and catalyse sustainable growth. Manufacturers that fail to fully harness the transformative power of frontier technologies in operations and supply chains will surely fall behind.

Although the pursuit of frontier technologies is not novel, the stakes are now higher than ever. The challenges associated with identifying and evaluating these technologies and integrating them into long-term strategies have grown more complex as the pace of innovation accelerates. Forward-thinking industries, technology leaders and academic institutions are pioneering such advancements. Yet, even with the growing accessibility of tools like generative AI, manufacturers still face a crucial question – how will frontier technologies drive real, measurable impact in day-to-day operations?

This white paper presents a bold yet actionable vision of one such frontier technology – AI agents. It additionally outlines methods by which this technology could be applied to create tangible value in industrial operations. The paper focuses on the transformative potential of two types of AI agents – virtual AI agents and embodied AI agents – and provides insights and case studies from leading industries while challenging conventional thinking and inspiring new strategies. Its aim is to highlight innovative perspectives to help manufacturers unlock the full potential of AI agents and spearhead operational transformation.

Executive summary

It's essential that manufacturers embrace frontier technologies to secure a thriving, sustainable future in manufacturing.

The manufacturing landscape is becoming increasingly complex, and this trend is projected to accelerate in the coming years. Labour shortages, rising cost pressures and shifting customer demands, geopolitical dynamics and decarbonization goals necessitate significant operational transformation.

Current technologies will be insufficient to drive the required levels of flexibility, sustainability and excellence needed to facilitate this change. To succeed, manufacturers can embrace frontier technologies that push the limits of innovation. However, navigating this rapidly evolving technological landscape is challenging, as many manufacturers need to address immediate operational needs and plan for the future of their operations.

Industrial operations are likely to evolve towards an artificial intelligence (AI)-centric model, where AI drives self-controlling, near-autonomous systems while empowering humans. While near-autonomous operations may become common in some industries, human involvement will remain crucial. The role of humans will be redefined, with workers transitioning from hands-on operators to orchestrators, stepping in when judgment or creativity is required. This shift will boost operational efficiency, allowing humans to focus on strategic tasks and ethical decision-making to drive innovation and growth.

In the broad landscape of frontier technologies, AI – and more specifically, rapidly evolving AI agents – have the potential to propel manufacturers towards this future, and unlock novel opportunities in operations across many industries. This report focuses on two types of AI agents: virtual AI agents and embodied AI agents. These agents are expected to enhance both digital applications and physical systems, and perform complex tasks with minimal human intervention.

- **Virtual AI agents – advancing autonomous software systems**: Virtual AI agents enable software applications to autonomously achieve defined goals in the digital environment, acting as assistants, advisers or automation agents. These agents support workers and can also independently control and steer processes and machinery.

- **Embodied AI agents – ushering in a new era of robotics**: Embodied AI agents equip physical systems, such as robots, with the ability to perceive and act within the physical environment, allowing for dynamic and complex movements. These advancements will be crucial for overcoming the current limitations of robotic automation.

Successfully navigating the transition to near-autonomous, AI-agent-driven operations requires a comprehensive, value-driven approach to technology adoption. Solutions should be scalable and aligned with long-term business objectives. Establishing strong organizational and technological foundations that support this vision will be crucial for manufacturers looking to capture the technology's full potential.

The insights presented in this paper are focused on manufacturing and founded on the collective expertise of the initiative community, drawing from consultations with senior executives and academic experts. Moving forward, the community will continue to work closely with manufacturing stakeholders across industries to deliver a global, comprehensive outlook on the future of industrial operations. This effort will concentrate on recent and future frontier technologies, with an emphasis on responsible transformation approaches.

Introduction

AI agents are transforming industrial operations, driving efficiency and unlocking competitive advantages.

As new frontier technologies emerge, manufacturers face the key challenge of discerning which innovations will bring lasting value at scale, and which are merely transient trends.

Frontier technologies have pushed the limits of what is possible in industrial operations over the past decades, significantly boosting productivity, reducing costs and improving the work environment. Innovations like robotics and the industrial internet of things (IIoT) have been instrumental in modernizing operations and laying the foundation for the next wave of breakthroughs.

Today, the technological landscape is evolving at an unprecedented pace. This progress is primarily driven by the exponential increases in computing power and breakthroughs in artificial intelligence (AI) society is currently witnessing. As new frontier technologies emerge, manufacturers face the key challenge of discerning which innovations will bring lasting value at scale, and which are merely transient trends. This creates uncertainty around where to focus development efforts and investments.

Overcoming these challenges is essential. Harnessing the value of frontier technologies is now vital for manufacturers as they seek to maintain a competitive edge and tackle industry-specific obstacles. To retain a leading position in the evolving landscape, companies must not only adopt these innovations but also understand the transformative impact on the future of operations. Success in this journey hinges on answering a few key questions:

- What will the future of industrial operations look like?
- Where is the real value in this transformation?
- Which frontier technologies will address key challenges?
- What steps need to be taken to realize value at scale?

Drawing on insights from experts and executives across operations and technology, this white paper provides a strategic perspective on these questions, with a focus on AI-agent-enabled transformation. It presents a forward-looking vision of AI-driven, near-autonomous industrial operations. It explores the role of AI agents in enabling this vision, specifically **virtual AI** and **embodied AI** agents, offering concrete examples and case studies to demonstrate their value. Additionally, it outlines the strategic imperatives necessary for successfully scaling these technologies. While AI agents hold transformative potential, it is crucial to recognize that they are not yet fully developed. Leading companies are running pilots to test their capabilities, with their at-scale impact to be realized in the coming years.

Although not covered in this white paper, other frontier technologies – such as biotechnology and quantum technology – are generating significant interest. These technologies hold the potential to revolutionize manufacturing operations, either directly or indirectly, but remain in earlier stages of development.

BOX 1

The two types of AI agents

Virtual AI agents

Software-based AI agents that operate entirely in the digital environment and enable digital applications to autonomously achieve defined goals

Embodied AI agents

AI agents integrated into physical systems – such as robots – that interact with the physical environment

1 The next leap: reinventing industrial operations through frontier technologies

Preparing for the challenges ahead requires operational transformation driven by frontier technologies.

Manufacturers face a complex operating environment with growing challenges:

- **Cost competitiveness**: Rising labour costs, supply chain disruptions and international competition necessitate improved efficiency and lowered structural costs.

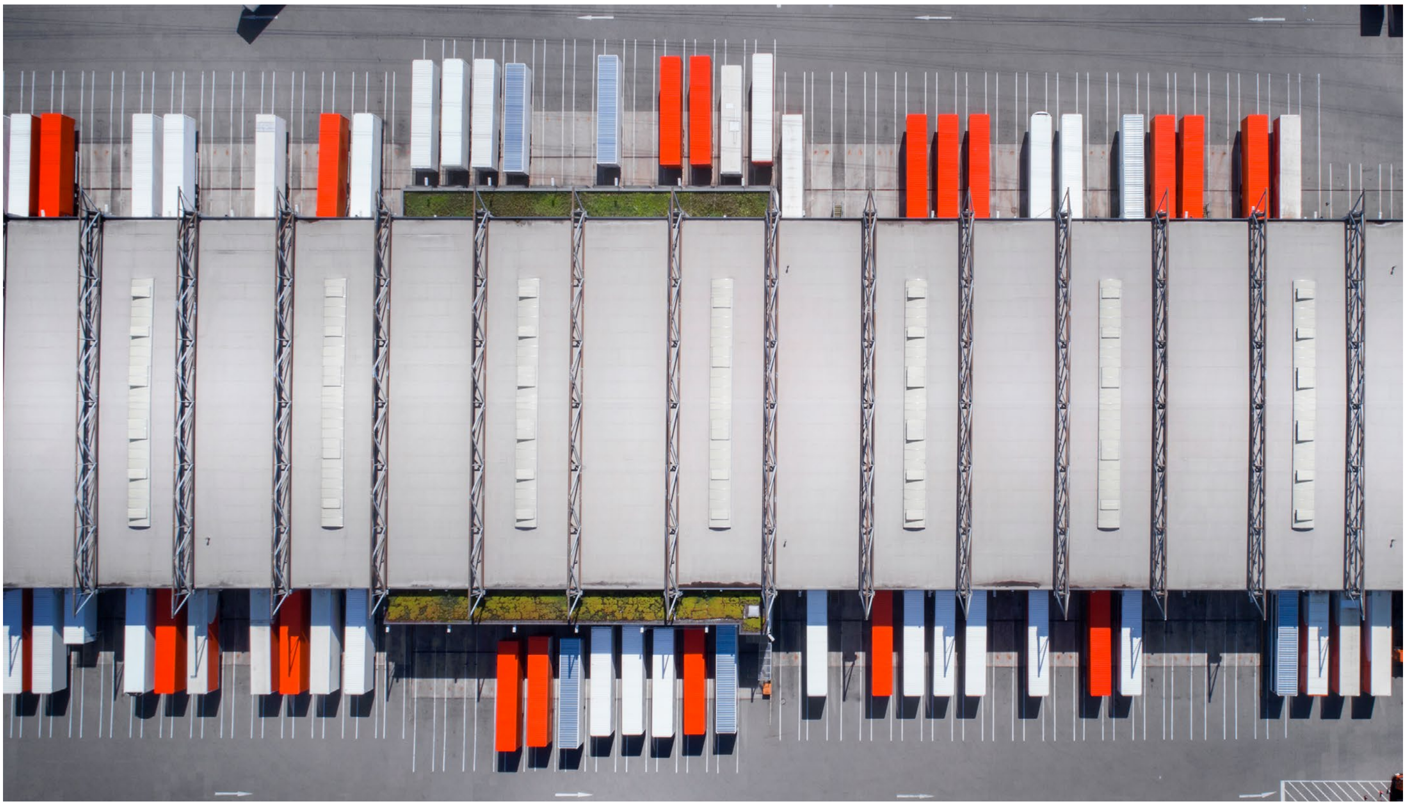
- **Labour shortages**: More than 2.1 million manufacturing jobs are projected to remain unfilled in the US alone until 2030,[2] driving workforce risks and productivity challenges.

- **Customer demands**: Consumers' expectations for greater customization and faster delivery drive the need for more flexible production systems and better demand forecasting.

- **Geopolitical dynamics:** Tariffs and fragmented production across multiple geographies hinder economies of scale, leading to greater complexity in supply chains, dispersed know-how and increased risks.

- **Sustainability**: To meet decarbonization goals, it's crucial to optimize energy and resource use while reducing emissions through robust supply chain management.

Addressing these challenges requires a shift in operational excellence, breakthrough innovation, structural optimization, supply chain diversification and investment in regional manufacturing clusters.



1.1 Entering the next frontier: the path towards self-control

> Although the extent of automation will ultimately depend on the return of investment, many factories may converge towards autonomy, driven by the need to remain competitive.

The industrial sector stands at a pivotal juncture. Frontier technologies, such as AI agents, are capable of performing complex activities. This paves the way for increasingly AI-driven, near-autonomous operations, within which many machines and AI-enabled systems will function with minimal human intervention. Success depends on cultivating a trusted human-machine interaction, where both collaborate seamlessly.

Currently, automation is often reserved for simple, repetitive tasks that still require manual oversight to ensure continuous operation. In the past, the expansion of automation was hindered by technological hurdles (such as an inability to handle unsorted flexible parts like cables automatically) and financial constraints. However, more advanced technologies and decreasing costs are poised to enable wider deployment across factories, with autonomous systems taking control of routine operations. These autonomous systems – encompassing machines, robots and virtual systems – may manage routine tasks ranging from material handling to quality control and production planning. Such systems may optimize and adjust production parameters on machines in real time to align with business needs, enhancing flexibility. Although the extent of automation will ultimately depend on the return of investment across industries and regions, many factories may converge towards autonomy, driven by the need to remain competitive.

The shift towards autonomy may also revolutionize factory design. Future AI-centric factories might prioritize machine-optimized layouts that enhance production efficiency and flexibility. For instance, valuable ground-floor space can be freed up by storing unfinished parts in automated multi-storage shelves, manual processes can be accelerated and performance monitoring can be centralized in virtual control centres rather than dispersed throughout the shop floor.

Self-controlling factories and supply chains will deliver significant improvements such as:

- **Efficiency**: Predictive analytics will shift operations from reactive to proactive management, anticipating issues and implementing necessary adjustments immediately. Real-time adjustments will enhance machine uptime, quality control and cost efficiency.
- **Flexibility**: Advanced robotics and AI will enable highly personalized manufacturing and swift reconfigurations, making production lines adaptable to varying product demands. Autonomous systems will self-organize for optimal factory layout and performance, further enhancing flexibility. They will also increase supply chain agility and responsiveness.
- **Sustainability**: Autonomous systems will optimize energy consumption and minimize waste. Real-time analytics will monitor environmental impacts, ensuring that sustainability goals are met without sacrificing efficiency.
- **Worker empowerment**: AI-driven tools and automation will enhance workforce capabilities and facilitate human-machine interactions, enabling workers to quickly understand production issues and make more well-informed decisions.

The transformation to near-autonomous industrial operations requires coordinated changes across both human and technological dimensions.

1.2 Redefining the role of humans: from operators to AI-enabled orchestrators

Human involvement will remain essential in industrial operations of the future, as workers may transition from hands-on operators to AI-enabled orchestrators who oversee autonomous systems and provide judgment or ingenuity as required. As machines advance in natural language comprehension, human-machine interactions will become more fluid and intuitive, enabling productivity breakthroughs. For example, one individual supported by assistant systems can supervise multiple functions such as quality, inspection and production simultaneously. Maintenance activities that require physical dexterity – such as checking for leaks or replacing parts inside a machine – may partially remain human-led but can be significantly augmented by virtual agents.

> In a future with largely self-controlling systems, humans may partner with machines, harnessing collaborative intelligence to focus on higher-value tasks.

In a future with largely self-controlling systems, humans may partner with machines, harnessing collaborative intelligence to focus on higher-value tasks, such as:

- **Strategic decision-making** involves using AI-driven recommendations to make business-critical decisions. For instance, in an automotive plant, AI may recommend adjustments to production schedules or shift planning. A human planner may weigh these recommendations against factors such as projected customer demand or current labour availability.

- **Performance supervision** involves monitoring and adjusting autonomous systems as needed. For instance, in a semiconductor plant, operators may monitor autonomous systems handling wafer fabrication. If performance metrics show yield deviations that systems cannot resolve, humans can step in to address the issue.

- **Continuous improvement** involves solving complex problems and optimizing processes. For instance, in a chemical processing plant, engineers may use AI to identify inefficiencies in mixing or reaction processes. They can then redesign workflows or machine configurations to optimize output and reduce waste.

- **Creativity and innovation** involve developing new production processes and rethinking factory layouts. For instance, in a consumer electronics plant, a maintenance worker might introduce creative ideas to streamline tool changes by mounting additional supports that have been employed in other industries.

BOX 2

Industry example: Shifting role of technicians and supervisors

A global wheel manufacturer has experienced a shift in the role of their technicians and supervisors with the introduction of a prescriptive AI solution for process parameter adjustment developed by a Cape Town-based AI solution provider. Instead of managing process details, technicians now focus on identifying root causes and driving continuous improvement by optimizing the plan-do-check-act (PDCA) cycle. Supervisors, in turn, are evolving into AI users, interpreting AI-driven insights and guiding operators towards more efficient problem-solving. This transition enables both operators and supervisors to concentrate on long-term, systemic improvements rather than routine, reactive tasks.

BOX 3

Industry example: Elevating planner roles with AI-supported decision making

A Fortune 500 technology manufacturer elevated the role of its planners from executors to architects of its supply chain decision-making process. Previously relying solely on humans, the company struggled with delayed decision-making, resulting in large inventories and long lead times. By harnessing an AI agent solution from a US-based decision intelligence company, they automated routine decisions in inventory management while routing exceptions to human experts with contextual data, analysis and recommendations. The platform optimized stock levels and ensured supply was matched to regional demand. As a result, 77% of agent recommendations were automatically executed and 90% were accepted without change.

This evolution will require manufacturers to anticipate a transition in workforce skills and cultural identity, making early engagement of operators in the transformation journey critical for success.

2 AI agents fuelling the transformation of operations

Virtual and embodied AI agents could drive the transition towards near-autonomous operations in both software and robotics.

Realizing the transformative vision of AI-centric operations requires a thorough assessment and evaluation of the potential of AI agents. Both virtual and embodied AI agents have the potential to deliver significant value, unlock new opportunities and drive the transition towards near-autonomous operations.

> **AI will transform from a data-centric front end to an agent-centric user end, relying on domain-specific data sources to optimize industrial operations. These domain-based agents will drive new growth of AI across different industries. The interactive agents will further transform the new large knowledge model, fostering the development of AI ecosystems with advanced technologies, tools and talents.**
>
> Jay Lee, Clark Distinguished Professor;
> Director, Industrial AI Center, University of Maryland

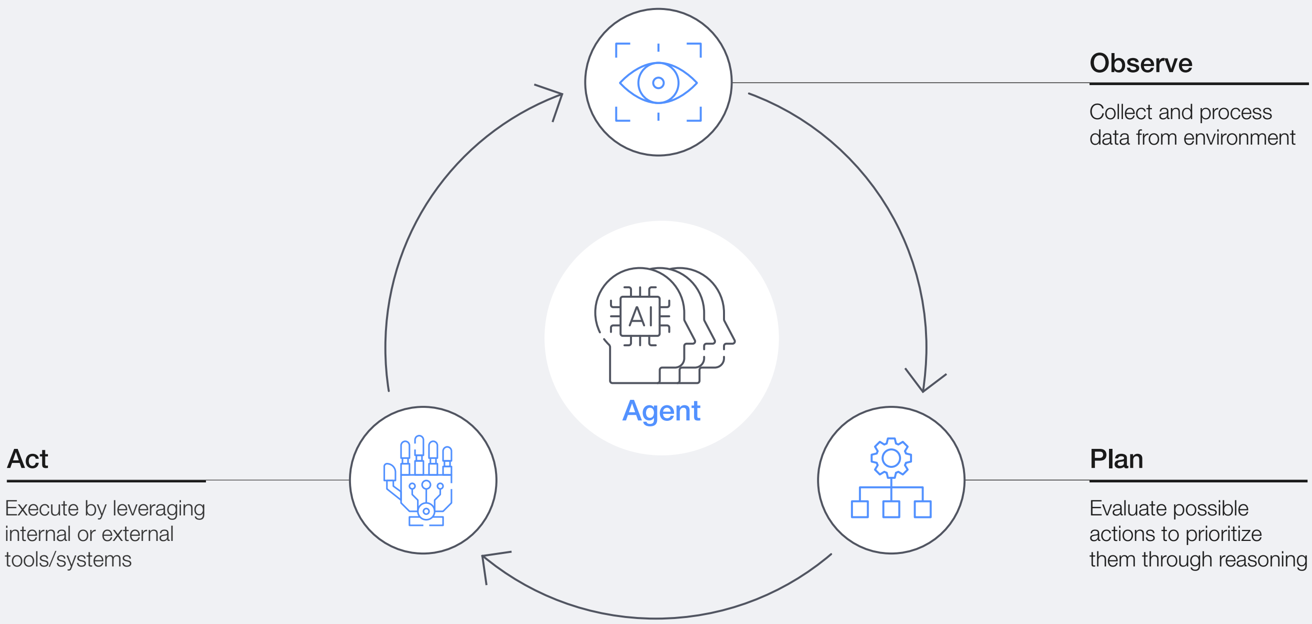
BOX 4 | The basics of AI agents

AI agents amplify the impact of large language models (LLMs) by giving them access to tools and enhancing their ability to observe, plan and execute actions.[3] Traditional AI algorithms, such as machine learning, are task-specific and require human input for defining tasks, providing data and interpreting results. In contrast, AI agents, once trained, can operate and achieve specific objectives autonomously, continuously observing their environment, planning actions and harnessing tools to execute complex tasks. AI agents function in a continuous **observe**, **plan** and **act** cycle, which makes them particularly valuable for operations. Each step is enabled by interfaces or modules:[4]

- **Observe**: Agents collect and process data from the environment, including multimodal data, user input or data from other agents. For example, an agent can perceive deviations in production quality and underlying parameters in real time.
  - Agent-centric interfaces: Agents require protocols, application programming interfaces (APIs) and specifically designed interfaces to input multimodal data or perceive real-time data from multiple sources.
  - Memory module: Agents have short- and long-term memory, which allows them to remember general knowledge, past actions and decision-making.
- **Plan**: Agents and their underlying LLMs evaluate possible actions to prioritize them through logical reasoning, in accordance with their objectives. In the example above, the agent reviews possible actions to improve quality and decides to change production parameters.
  - Profile module: Agents have defined attributes, identities, roles or behavioural patterns. The roles can be predefined, or agents can be flexible and dynamically adapt to new roles.
  - Reasoning module: Agents have limited reasoning capabilities. The underlying LLM is capable of decomposing the agent's prompts and returning an actionable plan. It extracts key insights and makes logical connections by replicating reasoning steps observed in training data. This enables agents to decide on the required next steps by breaking down complex tasks into small actions to achieve their objectives. Recent studies have shown that current LLMs are not yet capable of formal reasoning. Real-world solutions thus require other types of AI and solvers and cannot solely rely on existing LLMs.[5]
- **Act**: Agents execute actions by harnessing internal or external tools and systems. For example, an agent accesses the machine controller and changes the defined machine parameters.
  - Action module: Agents decide which tools to use, using access mechanisms such as APIs, system integrations or other agents as needed.

Functioning in this cycle, agents continuously learn from self-reflection or external feedback. Through goal-oriented learning approaches, such as reinforcement learning, agents continuously adapt and refine their strategies over time. This makes them particularly valuable in complex, dynamic environments where conditions and objectives are constantly shifting. Such environments can be found widely across industrial operations. As part of multi-agent systems, in which specialized agents work together by dividing complex problems among themselves, they can automate entire processes end-to-end.

AI agents function in a continuous observe, plan and act cycle



Source: Boston Consulting Group (BCG).

2.1 Virtual AI – paving the way for autonomous systems

Virtual AI agents can manage a wide range of software-based tasks, from routine operations and research to advanced analytics and task automation. In industrial operations, they can enhance responsiveness, improve execution quality, boost productivity and reduce operational mistakes. Unlike traditional machine learning programmes, they can make context-sensitive decisions in real time and adapt through feedback loops. These agents have applications across all operation functions, including production, maintenance, quality, engineering, logistics and planning.

The maturity of virtual AI agents can be categorized into three levels: assistant, recommendation and automation. The distinct objectives at each maturity level are pursued by specialist agents:

FIGURE 1 **The four types of virtual AI agents**

Maturity level	**Assistant** (executing manual tasks)	**Recommendation** (proposing scenarios and actionable insights)	**Automation** (autonomously performing activities)
Specialist agents	**Knowledge agent**	**Adviser agent**	**Automation agent**
Meta agents		**Meta agent**	

Source: Boston Consulting Group (BCG), World Economic Forum.

Knowledge agents support workers as intelligent assistants. They analyse and synthesize vast amounts of data to provide real-time operational insights, flag anomalies and create content such as reports and code. By accessing multiple tools and real-time data sources, such as machine logs and sensor data, they add value to functions that require quick insights – for example, in maintenance, quality and logistics. They can also support engineering with machine code generation.

Adviser agents go further by generating real-time scenarios to address issues, and recommending actionable insights. They continually refine their recommendations based on real-time feedback, enabling them to learn autonomously and adjust actions such as machine parameter setting, workforce management, production planning and factory layout optimization. They also suggest the best possible scenario based on their optimization objective and received feedback, empowering users to align decisions with business priorities.

Automation agents act independently, executing optimal actions without human input. They adapt to new situations through real-time feedback without explicit retraining, allowing them to autonomously optimize machine performance, adjust production parameters, recode instructions or modify production plans. They surpass existing RPA (robotic process automation) by automating not only individual tasks but also entire human activities that require understanding, planning and execution.

Meta agents orchestrate specialist agents in the context of multi-agent systems to achieve broader objectives, enabling area- or even factory-wide steering. The long-term vision for meta agents is to consolidate knowledge and automate end-to-end supply chains by integrating diverse specialized agents. Within a factory, these agents could cover an entire production process or group of machines. While specialist agents are already being piloted across industries, meta agents require enterprise-wide AI and further development before real-life implementation.

Virtual AI has a significant impact across all manufacturing and supply chain functions, from logistics to production, as well as support functions such as maintenance, quality and engineering. The two use cases described below – **production process parameter setting** and **real-time production planning** – illustrate the agents' capabilities.

> Virtual AI agents have applications across all operation functions, including production, maintenance, quality, engineering, logistics and planning.

TABLE 1 Application of virtual AI agents in production process parameters setting and real-time production planning

	① Production process parameters setting	② Real-time production planning
Use case description	**Achieving optimal setting of machine parameters** (such as temperature and pressure) is a key goal for manufacturers across all industries. The complexity of optimizing various process parameters under specific external influencing factors forces manufacturers to rely heavily on operator experience. AI agents are transforming this process to improve overall equipment effectiveness.	**Real-time production planning** is critical for manufacturers to meet demand, reduce lead times and optimize resource use. However, the complexity of balancing capacity, inventory, labour and external factors often requires manual adjustments by experienced planners. AI agents are transforming this process by streamlining decision-making and improving flexibility and responsiveness to changing conditions – ultimately enhancing overall production efficiency.
Knowledge agent	**Parameter knowledge agents** harness machine and process parameters and production output data (such as quality validation, material properties, and maintenance and quality reports) to identify optimal equipment settings for enhanced machine performance. The agent can be activated by workers via voice input or can raise alerts when predicting deviations. It continuously refines its analysis based on worker feedback. It also assists decision-making by estimating the potential value and cost impact of potential adjustments.	**Planning knowledge agents** serve as foundational tools that gather and synthesize data from multiple sources, such as historical production performance, demand forecasts, inventory levels and resource availability. By harnessing this data, an agent provides planners with actionable insights. It can analyse past trends to identify potential bottlenecks, recommend best practices and highlight opportunities to streamline production processes. Planners can query the agent to retrieve detailed analysis or predictive insights, making it a valuable decision-support tool. Over time, it refines its knowledge, continuously improving the accuracy and relevance of its insights.
Adviser agent	**Parameter adviser agents** continuously monitor machine performance, detect real-time deviations and recommend setpoint improvements to achieve desired production goals. Operators can validate the recommended settings and corrective actions. The agent refines its recommendations over time by integrating real-time worker feedback and assessing performance outcomes.	**Planning adviser agents** build on the capabilities of the knowledge agent by continuously monitoring real-time production and forecast data. They detect potential deviations, such as delays, resource shortages or equipment downtime, and recommend proactive adjustments to the production plan. These recommendations can include rescheduling, resource reallocation or inventory adjustments to ensure operational targets are met. The agent learns from the planner's validation and feedback, allowing it to improve its predictions and better anticipate future challenges. This adaptability augments its ability to optimize production planning.
Automation agent	**Parameter setpoint automation agents** continuously track machine performance, identify anomalies in real time and autonomously adjusts setpoints or take corrective actions. They adapt and self-correct parameters based on current production priorities without requiring human intervention. The agent can also work with digital twins, incorporating necessary external inputs such as customer demands into the digital twin to support business decisions. Although pilots in series production are still pending, a research study has demonstrated how LLM agents can control and steer operations remotely, either with human oversight or through AI agents in a digital twin.[6]	**Planning automation agents** take the next step by autonomously managing production schedules in real time. They respond dynamically to production events like machine breakdowns, labour shortages or fluctuations in demand. The agent continuously updates the production plan, reallocates resources and reschedules tasks to ensure the overall production process remains efficient. Unlike the adviser agent, the automation agent acts independently to adjust, only requiring human oversight for major exceptions or strategic decisions.
Meta agent	**Meta parameter agents** oversee and orchestrate multiple dedicated machine parameter agents, synchronizing setpoints across various machines. This agent autonomously coordinates actions to ensure an optimized production flow, preventing bottlenecks and dynamically adjusting the system to optimize overall performance.	**Meta supply chain agent** oversees multiple planning agents that focus on specific areas such as labour, inventory, or capacity. It coordinates these agents to ensure that the entire production process remains balanced and optimized. By dynamically adjusting priorities and resources across various departments, the meta agent ensures that the production plan aligns with broader organizational goals and avoids conflicts between localized planning decisions.

TABLE 2 | Snapshot of sample case studies of virtual AI agents

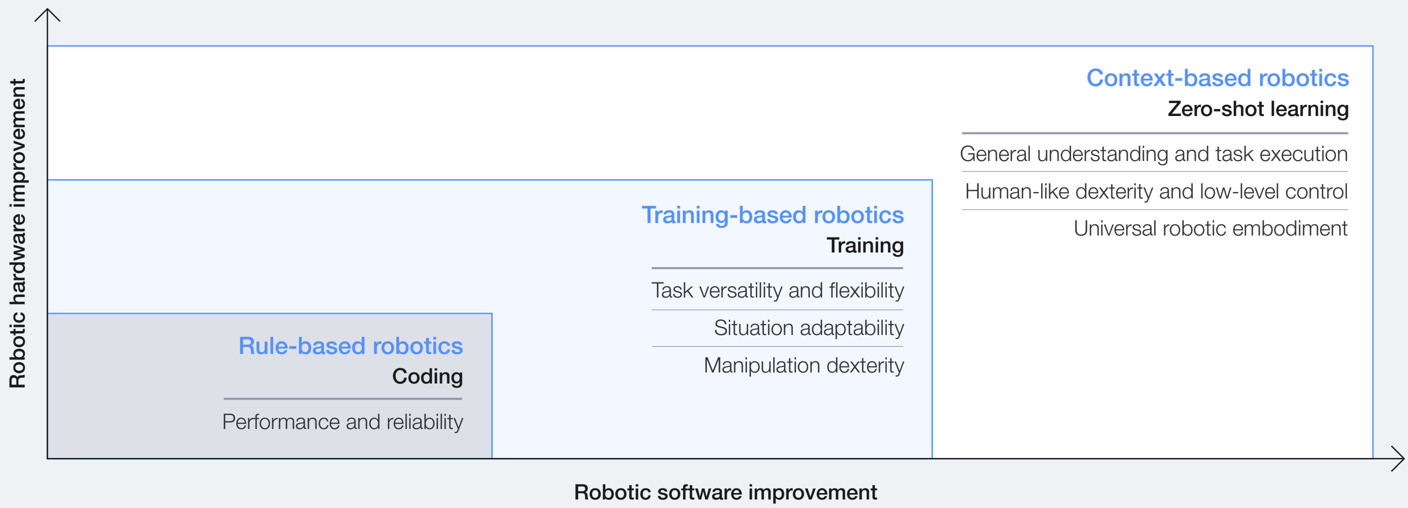
Use case	Challenge	Solution	Benefits
Autonomous control agent for steel manufacturer	Steel manufacturer KG Steel faced two main challenges: 1) high liquified natural gas (LNG) energy costs to operate furnaces and, 2) discrepancies in the product quality arising from a skill gap caused by an ageing workforce. To meet the desired quality of coils, operators must adjust the heating settings of furnaces while accounting for varying production environments. Inefficient heating process control causes excessive use of LNG.	A South Korea-based AI software provider developed a deep learning model predictive control optimization model that executes "what-if" scenarios based on possible control patterns, and assesses them in a digital twin to select the optimal controls. Initially, the agent acted as adviser, providing operators with recommendations on optimal control settings. Partial automation of furnace operations was later achieved via system integration and direct feeding of agent output into the furnace control system.	The agent has decreased LNG consumption by approximately 2%, while reducing differences in the product quality.
Planning AI agent for global brewer	A global brewer aimed to improve its planning process and forecasts. The current approach, known as post-game analysis, entailed continuously assessing past forecast inaccuracies and their root causes. This was tedious and required expert knowledge that dissipates over time.	Post-game analysis is increasingly conducted by LLM composite agents that integrate a sequence of atomic agents to perform complicated exercises. They are trained on post-game "recipes" built by planning experts, learn continuously from feedback to improve results over time and can be used in cross-functional planning processes. Beyond productivity, the agents enhance knowledge and expertise in an organization.	By using the agents of a US-based planning solution provider, the brewer achieved 70% touchless demand and supply planning. They additionally issued a resolution for feasibility checks. This percentage is expected to increase further as complex LLM/agent capabilities are added and further enhanced. Key success factors for adoption and scaling are the quality of the data, the ability to capture the decision-making logic of planners, plan explainability and trustworthiness of outcomes. Based on these criteria, the mid-term ambition is to achieve 90% automation scope and global scaling across markets.
Autonomous quality control AI agent	As a globally recognized digital lighthouse,[7] Siemens Electronics Work Amberg (EWA) has set the ambitious goal of achieving a first pass yield (FPY) exceeding 95% with a defect per million connections (DPMC) below 10 per production batch. This is a significant challenge, given that a circuit board can have up to 3,800 quality features to monitor. So far, the FPY target has been unachievable as employees have not been able to consistently make the right decisions given the time constraint and stress.	To achieve this objective, EWA developed a patented autonomous quality control AI agent in collaboration with RIF Institute for Research and Transfer. This advanced agent, harnessing self-organizing maps, assists employees in correctly setting up the solder paste printer for the first production run. This reduces process times in a complex, multi-parameter task that typically requires significant experience. As process parameters are continuously improved, the agent adapts by accounting for parameter changes, resulting process behaviour and prior adjustments. This enables it to continuously learn and optimize the unknown behaviours of the solder printing process. After the testing phase, the agent will be able to autonomously adjust the parameter settings.	Multiple studies have consistently demonstrated high-quality product output while simultaneously reducing the solder paste printer's process time by up to 50% compared to the cycle time. The next phase of development involves transforming the agent into an edge application for rapid scalability. A key requirement for this advancement is integrating the quality inspection gates into the comprehensive digital twin of the process.

2.2 Embodied AI – igniting a new era in robotics

AI is not only transforming software but also automating physical workflows. Embodied AI integrates AI into physical systems such as robots, allowing them to perceive and interact with their environment through dynamic and complex movements. The agents see the world via sensors (for example, cameras, radar, lidar and microphones) and execute actions through actuators such as advanced grippers. Applied to industrial operations, these agents enhance the capabilities of existing robotic systems, enabling more sophisticated automation. By doing so, they expand the automation scope, overcoming traditional challenges such as those associated with handling unstructured environments or manipulating unstable objects.

FIGURE 2 **Three types of robotic systems**

Robot capabilities enabled by embodied AI



Source: Boston Consulting Group.

Notably, three types of robotic systems have emerged: rule-based, training-based and context-based (Figure 2). This evolution has been driven by improvements in both robot hardware and software. The hardware is becoming more capable, reliable and flexible. At the same time, the software is advancing, with improvements in foundation models and technologies (such as reinforcement learning).[8] A five-fingered robotic hand with 24° of freedom can perform complex tasks with an unprecedented level of dexterity.[9] This is made possible by the various data sources that can be harnessed to train AI-enabled robots:

> Embodied AI integrates AI into physical systems such as robots, allowing them to perceive and interact with their environment through dynamic and complex movements.

- **Real robot data**: This data is collected from the robot motion controllers and can also be generated by human-guided robot teleoperation. Although real robot data is the most accurate, it is limited because it can only be gathered from deployed robot fleets.

- **Synthetic robot data**: This data is created in simulated physics-based environments and is available in infinite supply. While any scenario can be simulated, a simulation-to-reality gap is expected to remain due to the diversity of the real world. This means real robot data will still be necessary for validation. For example, Foxconn trains robots in its virtual factory, using digital twins to generate synthetic data for model training and to teach robotic arms how to see, grasp and move objects.[10]

- **Internet-scale human data**: Online data, including human videos, is highly diverse, and equips AI with a foundation for understanding the world. It provides valuable information on how humans interact with objects and how objects behave. Imitation learning allows the latest models to learn these skills by mimicking human actions.

The discussion of the three robot types enabled by embodied AI centres on these software advancements, which harness advanced datasets:

Rule-based robotics: Beginning in the 1960s, industrial robots operated under rule-based systems, following “if… then” instructions that were manually coded by experienced robotic engineers. Complex

automation solutions required individual programming of each robot. These robots were limited to simple, repetitive tasks, allowing for minimal flexibility.

Training-based robotics: Embodied AI is a major technological breakthrough in robotics. The convergence of robotics, machine learning types such as reinforcement learning (RL), and advanced vision systems has transformed automation. By giving robots an understanding of the world, embodied AI enables new applications like bin picking. Unlike rule-based systems that depend on manual coding, AI-enabled, training-based robotics can now learn skills via RL in a trial-and-error approach in physical or simulated environments.

Context-based robotics: Context-based, autonomous robotics are built on robotics foundation models (RFMs) and have a general understanding of the world.[11] Because they require neither coding nor training by manufacturers, they can lead to a paradigm shift in robotics – that is, zero-shot learning. This considerably reduces the effort required to programme or teach these robots, opening the way to new, highly complex applications such as handling cables and addressing unforeseen events. RFMs are still in the development phase and are expected to break through in the coming years.

TABLE 3 **Benefits and examples of the different robot types enabled by embodied AI**

Robot type	Benefits	Example
Rule-based robotics 	– **Performance and reliability:** Robots execute repetitive tasks with defined precision and speed, based on their coded robot programme.	The vast majority of today's global robot fleet is rule-based, including industrial robots in assembly lines and automated guided vehicles (AGVs) in logistics. For repetitive tasks that do not entail deviation or special requirements, such as automated assembly lines of medical products, rule-based robots will likely stay the norm in the future.
Training-based robotics 	– **Task versatility and flexibility:** Robots understand the manufacturing world they have been trained in, giving them the necessary flexibility to adapt to different environments and the dexterity to handle known objects and perform versatile tasks. For example, a kitting robot can now handle a large variety of distinct parts, applying its learned skill library. – **Situation adaptability:** Robots can autonomously understand and solve unforeseen events in their trained domain by executing the required actions. For instance, if a screw gets stuck, robots can resolve the issue independently, significantly enhancing system reliability. Beyond articulated robots, embodied AI models enhance the capabilities of autonomous mobile robots (AMRs) for material transport drones and other robot types. – **Manipulation dexterity:** Robots can learn to move objects with dexterity, enabling them to conduct advanced movements such as contact-rich assembly of multiple gears, for example.	Kitting robots in a warehouse can handle a diverse range of parts of varying dimensions and characteristics. Previously, kitting operations required manual intervention or multiple robots to manage different part sizes, lowering the return on investment. For example, Otto Group, an online retailer founded in Europe, has deployed AI-controlled robots in its fulfilment centre to handle the order-picking process. Thanks to its AI capabilities, the robot can process a wide variety of shapes, colours and quantities, which previously required human hand-eye coordination for items such as textiles.[12]

TABLE 3 | **Benefits and examples of the different robot types enabled by embodied AI** (continued)

Robot type	Benefits	Example
Context-based robotics	– **General understanding and task execution:** Robots harness their general understanding of the world to autonomously generate any action and perform any task according to the situation. They can reason, plan and act based on the instructions received and the environment. Additionally, they can receive natural language instructions from technicians – for example, when asking for validation on how to grasp a particular object. This significantly improves finetuning in the factory and reduces the required skillset. – **Human-like dexterity and low-level control:** The models enable intuitive movements (for example, opening an object) and fast low-level control, adapting to any situation. They are expected to be able to handle flexible parts, such as cables, and cope with complex physics, such as moving liquid in a closed container. – **Universal robotic embodiment:** General RFM can embody any robot form, including humanoids, articulated robots or mobile robots, allowing for universal use of the models. The development of RFMs will be a breakthrough in robotic capabilities, especially for humanoid robotics. This is due to the large amount of human data that already exists to facilitate training of the human form factor. Additionally, because the world is built for humans, these robots will have a huge array of potential applications beyond operations.	Humanoid robots are a prominent example of context-based robotics, which has emerged in recent years. BMW is piloting the use of humanoid robots for assembly preparation in its Spartanburg plant.[13] The human form factor brings multiple benefits that can also be applied to operations, such as in the reuse of existing workstations. The future of humanoids in operations remains uncertain, however, as their human shape drives significant complexity that is not needed on a factory shop floor, such as bi-pedal locomotion instead of wheels. Even so, the underlying RFM will bring a breakthrough in operations, as it can embody any robotic systems, regardless of form.

> **The effect of virtual and embodied agents on industrial operations will be a tectonic shift, recasting how AI agent systems are built and function. However, as the futurist Paul Saffo noted, ‘Never mistake a clear view for a short distance’. We are still in the infancy stage of understanding these agents’ potential. Generative AI is not intelligence in a box – it doesn’t truly reason and can’t solve complex optimization problems alone. To safely deploy robots in dynamic, human-inhabited environments, combining large language models, vision language action models and other AI modalities along with engineering is essential, ensuring proper guardrails are in place for reliable, effective solutions.**
>
> Anthony Jules, Co-Founder and Chief Executive Officer, Robust.AI

Manufacturing companies are beginning to integrate virtual and embodied AI agents into their operations, as showcased by the pilots discussed above. Although AI agents are still in the early stages of development and require further refinement for large-scale deployment, it is essential for industry leaders to consider the foundational elements necessary for supporting their successful implementation and integration into existing systems.

3 Strategic imperatives for industrial operations transformation

Transformation success hinges on a value-driven, end-to-end approach, grounded in strong organizational and technological foundations.

The crucial considerations and steps of the AI journey described in *Harnessing the AI Revolution in Industrial Operations: A Guidebook*, published in October 2023, provide the starting point for manufacturers preparing to implement AI technologies at scale. However, the scope of considerations for frontier technologies, including AI agents, extends beyond those highlighted in the guidebook. To enhance industrial operations and meet new standards, manufacturers need to remain at the forefront of frontier innovations, prioritize value-driven strategies and develop robust organizational and technological foundations.

3.1 Paving the way for successful use of AI agents in industrial operations

The transformation journey begins with the development of a clear vision for the future of operations that's aligned with the organization's long-term objectives. The journey's success depends on how well the reason behind the transformation is articulated.

Although AI agents and frontier technologies are provoking great excitement, it is essential to avoid being captivated by technological advancements alone. Technology, by itself, will not generate value and is only one of several success factors for sustainable transformation. For example, embodied AI-enabled automation solutions should be pursued only if they bring a significant return on investment or can contribute to larger applications.

Successful manufacturers have adopted a value-driven, end-to-end perspective. Furthermore, while proving value quickly is important to build trust within the organization, ensuring the scalability of the solutions from the outset is crucial.

3.2 Staying at the forefront of AI agent innovations

The frontier technologies poised to disrupt operations are rapidly evolving. The field of AI agents is still developing, with new capabilities expected in the coming years. Maintaining leadership in the deployment of these innovations requires a sustained, systematic effort.

Identifying and evaluating AI-agent innovations should be an organization-wide endeavour, as their impact extends beyond operations to areas such as engineering, procurement and IT, as well as the overarching business strategy. Companies should apply a systematic approach to reviewing such new technologies and assessing the maturity of their current operations, to facilitate the preparation, implementation and scaling of processes.

3.3 Building the foundations: organizational and technological

The field of AI agents is still developing, with new capabilities expected in the coming years. Maintaining leadership in the deployment of these innovations requires a sustained, systematic effort.

Strong organizational and technological foundations are essential for a successful operational transformation and the use of AI agents at scale.

Organizational foundations

- **Governance**: Tailoring the organizational structure and operational processes to a company's specific needs is crucial to support the transformation. To fully capture the value of AI agents, companies must review and adapt current processes and work procedures.

- **Skills and capabilities**: To unlock the full potential of AI agents, companies will need a broad set of skills and capabilities. This may include specialized expertise (such as prompt engineering) that the organization currently lacks and may need to build from the ground up. Additionally, to optimize AI agent use, companies must recognize and understand the technology's limitations. Supporting employees through upskilling and reskilling opportunities is also key, allowing them to grow along with the company. As these shifts elicit cultural changes, paying attention to employees' emotional skills may further facilitate a smooth transition.

- **Change management**: To succeed, change management must be led from the top of the organization, engaging all workers in the transformation. Building trust in the selected technologies through transparency and open communication early in the process is crucial to cultivating a culture of change. Developments in work practices and cultures influence how new and old roles, as well as new and existing talent pools, collaborate. Maintaining a continuous improvement mindset throughout the process ensures adoption and value realization.

- **Ecosystem partnering**: Collaboration is an essential enabler for success, due to each technology's inherent complexity and the depth of expertise required. The challenge is magnified when dealing with technologies that lack commonalities. For instance, embodied AI and virtual AI require different types of expertise and partnerships.

- **Legal compliance**: As the regulatory landscape matures, manufacturers must ensure that AI and other technologies are used responsibly. They must carefully assess associated risks before implementation. For example, AI agents could grant access to data that should remain restricted, so companies must evaluate the potential risks of making certain information widely available.

> **Frontier technologies, especially AI, help companies to enable tremendous value. To stay at the forefront, organizations must embark now on a journey from digital to adaptive towards autonomous operations. Success in this transition requires a well-defined strategy for a clean, digital core and data foundation, and a transformative organizational mindset, converging the traditional silos of operations. This will not only lead to a competitive advantage but also prepare companies for the major challenges of our time.**
>
> Dominik Metzger, Senior Vice-President and Global Head, Software Engineering Digital Supply Chain, SAP

> Manufacturers should stay ahead in the development of an enabling technology foundation. Achieving convergence of IT and OT will be crucial to unlocking the full potential of AI

Technological foundations

Manufacturers should stay ahead in the development of an enabling technology foundation. Achieving convergence of IT (information technology) and OT (operational technology) will be crucial to unlocking the full potential of AI. While these enabling technologies form the foundation of modern automation and digital transformation, they are not standalone value drivers. Key technological foundations include:

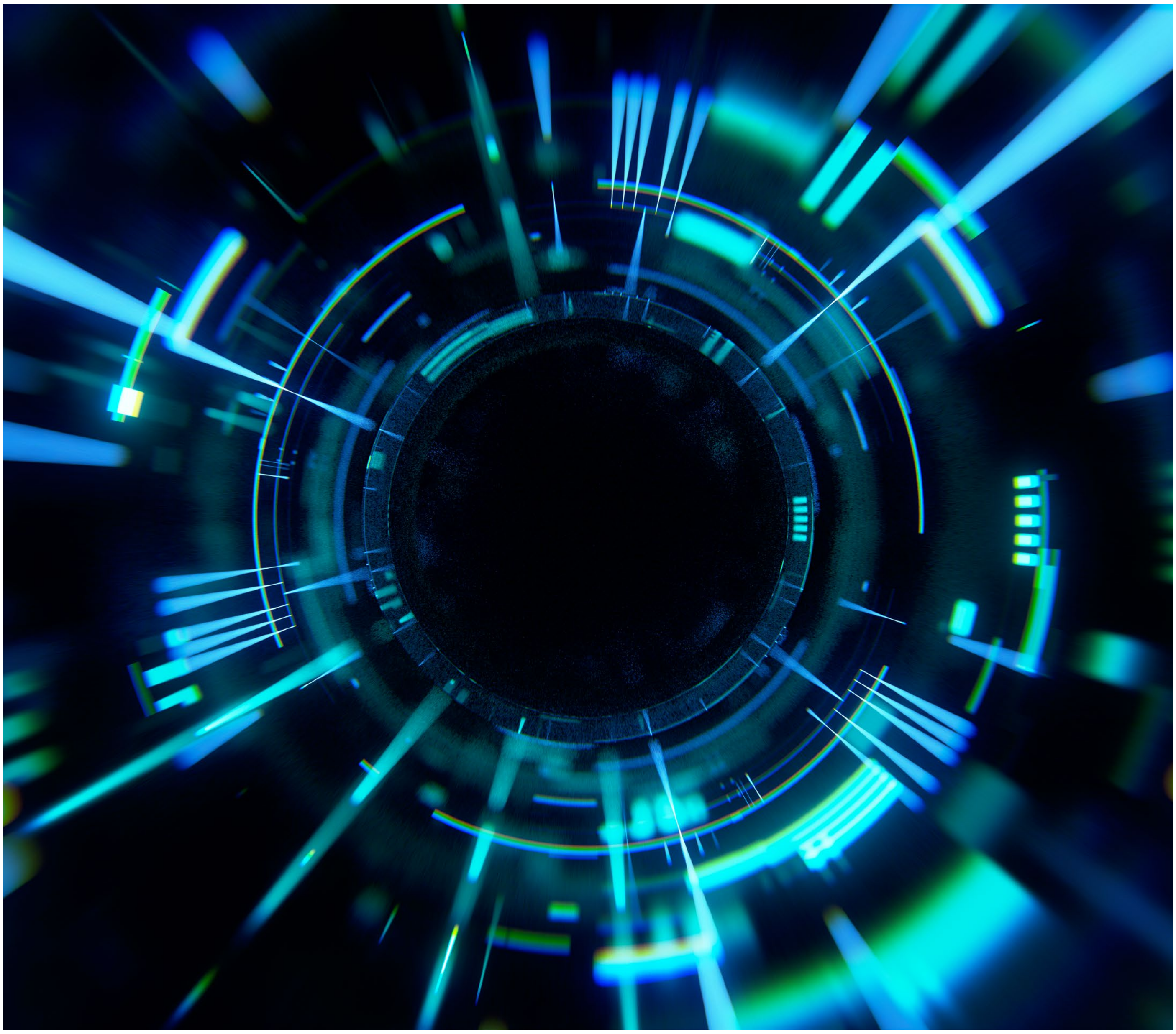
– **Data sourcing and processing**: AI agent applications require readily available and accessible data in the right format, appropriate data-processing infrastructure and data governance.

– **Applications and user interfaces**: User-friendly AI agent interfaces are critical for promoting adoption by operators. Interfaces should be intuitive and developed in collaboration with operators to maximize usability and engagement.

– **High-performance computing**: AI applications and advancements in simulation require significant computing power for timely data processing. Large-scale model training is typically conducted on cloud platforms that are commoditized by hyper-scalers. The emergence of on-premises edge computing has reduced traffic to the cloud by enabling computation directly on the factory floor, thereby enhancing energy efficiency and reducing latency in AI applications.

– **Connectivity**: Access to real-time data is crucial for highly automated environments including digital and robotic applications. This is achievable through advanced wired or wireless networks such as 5G networks.

– **Cybersecurity**: With end-to-end digitization, AI-enabled cybersecurity has become increasingly important for securing data and IT/OT systems, and combat agent-based threats. Companies need a comprehensive cybersecurity strategy to protect sensitive data and intellectual property in operations.



Conclusion

The impact of AI agents is expected to be significant in industrial operations. Recognizing this potential, leading manufacturers are conducting state-of-the-art pilots. The investments and early outcomes of these pioneering efforts highlight the tremendous transformative potential of AI agents. They are not only enhancing efficiency but also fundamentally reshaping the competitive landscape of global industries. In the near future, they are likely to become an essential foundation of most factories worldwide, offering manufacturers a pathway to AI-driven, near-autonomous operations.

While this white paper focuses on AI agents of two types – virtual AI and embodied AI – additional frontier technologies are expected to reshape operations. Additive manufacturing, quantum technology, biotechnology and enabling technologies such as 5G and edge computing are already on the horizon. To unlock the potential, manufacturers must form pragmatic insights into the comprehensive value impact of these innovations.

Along with their promise, AI agents bring challenges related to security, compliance, social responsibilities and infrastructure requirements. A collaborative approach among stakeholders – including business, academia and policy-makers – to exchange best practices and share insights is crucial for responsible transformation. The aim of this document is to encourage industry leaders to take a holistic approach to assessing the value impact of AI agents and other frontier technologies in their operations, and to prioritize responsible adoption.

Looking ahead, the World Economic Forum will continue to shed light on the latest frontier technologies and innovations in industrial operations, while also providing a unique platform for collaborations and experimentation among industry leaders, technology experts and academics. These collaborations will explore the maturity and value potential of frontier technologies at scale across many industries and end-to-end value chain functions, to unlock value for companies, society and the environment.

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