THE 2024 WORLD MANUFACTURING REPORT

NEW PERSPECTIVES FOR THE FUTURE OF MANUFACTURING: OUTLOOK 2030

WORLD MANUFACTURING FOUNDATION

Please use the following format for references and citations:
2024 World Manufacturing Report – New Perspectives for the Future of Manufacturing: Outlook 2030

The views expressed in this publication are the sole responsibility of the World Manufacturing Foundation and do not necessarily reflect the opinion of the experts and the organisations to which the experts belong.

Designations such as “developed”, “industrialised”, and “developing” are intended for statistical convenience and do not necessarily express a judgment about the state reached by a particular country or area in the development process.

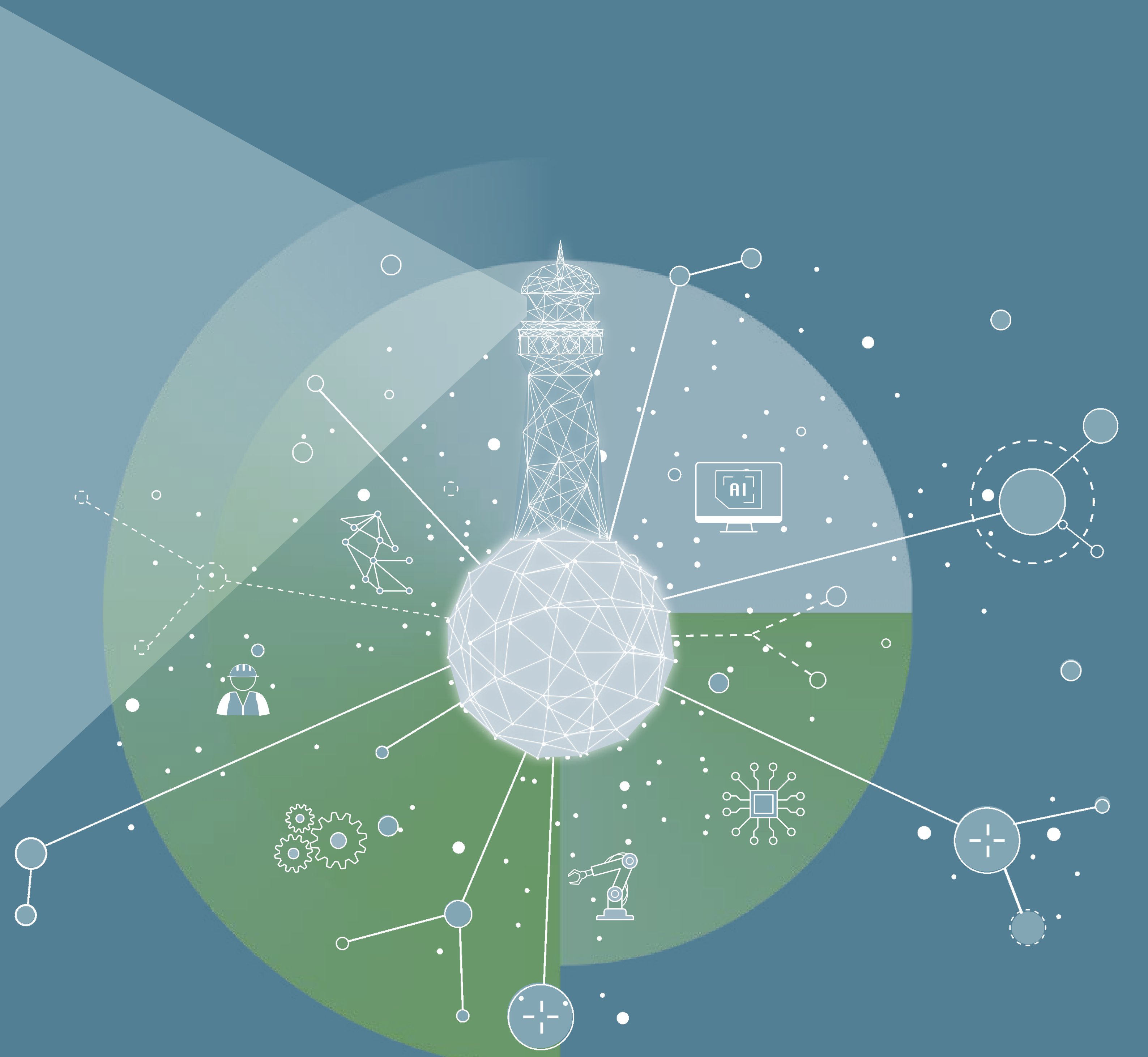
More information on the World Manufacturing Foundation can be found at www.
worldmanufacturing.org

ISBN: 978-88-947786-4-9

WORLD MANUFACTURING REPORT

2024

NEW PERSPECTIVES FOR THE FUTURE OF MANUFACTURING: OUTLOOK 2030


AI

Foreword

Dear Readers,

With the mission of spreading an industrial culture worldwide focused on improving manufacturing's role as a dynamic and positive driver of economic equity and sustainable development, the *World Manufacturing Foundation (WMF)* organises several international activities and events annually. The *World Manufacturing Forum* is its flagship event, where industry, academia, and governments from around the world come together to exchange their views and share their visions for a 360-degree view of the future of manufacturing, including its challenges, issues, and opportunities for positive change.

The *World Manufacturing Forum* serves as an open and independent platform for policy experts to assess their national, regional, and state industrial policies with a global perspective, for industrial leaders to benchmark their business practices internationally, and for eminent academic and research innovators to listen carefully to and discuss the wide-reaching calls for applied research and technological advancements to support the global manufacturing sector in playing its key role as the backbone of economic development and social prosperity for many nations.

As part of the *World Manufacturing Forum*, an annual whitepaper, the *World Manufacturing Report*, has been published and presented during the event since 2018 to examine relevant topics for the global manufacturing sector (from skills to key enabling technologies to innovative business and operating models), introducing their facts & figures and offering key recommendations on how to address them to create defensive positions and distinctive competitive advantages. For this year, the 2024 *World Manufacturing Report - New Perspectives for the Future of Manufacturing: Outlook 2030* - presents a global strategic analysis and forecast of the (geo)political, economic, social, technological, legal, and environmental trends and tipping points that are shaping or will be shaping in the following years all manufacturing industries worldwide with a horizon towards 2030, providing as in previous Reports 10 Key Recommendations for those actions needed for futureproofing manufacturing operations and supply chains in the face of a present and foreseen volatile, uncertain, complex, and ambiguous (VUCA) business environment for the sector.

The *World Manufacturing Foundation* and the *Editorial Board* of the 2024 *World Manufacturing Report* believe that the findings and recommendations presented in this whitepaper have the potential to provide actionable insights and measures for policymakers and industrial leaders to enhance the sustainability and resilience of manufacturing operations and supply chains to promote a future that ensures economic, social, and environmental prosperity for all, even in the face of adversity.

We thank the 2024 *World Manufacturing Report Editorial Team* and *International Advisory Board* for their valuable contributions to the creation of this whitepaper.

Prof. Marco Taisch
Scientific Chairman
World Manufacturing Foundation

Prof. David Romero
Scientific Vice-Chairman
World Manufacturing Foundation

WORLD MANUFACTURING REPORT

2024

NEW PERSPECTIVES FOR THE FUTURE OF MANUFACTURING: OUTLOOK 2030

Index

Executive Summary

The 2024 World Manufacturing Report on "New Perspectives for the Future of Manufacturing" examines the (geo)political, economic, social, technological, legal, and environmental trends shaping global manufacturing with an Outlook towards 2030.

Over the years, the World Manufacturing Reports have outlined significant manufacturing trends and provided recommendations to assist governments and industries in identifying and prioritising critical actions for sustainable industrial development that are likely to promote a future that ensures economic, social, and environmental prosperity: from exploring the new skills for the future of manufacturing – to embracing a new age of manufacturing based on artificial intelligence and intelligent automation – to digitally enabling the emerging circular manufacturing paradigm – to supporting the redesign of supply chains for resilience – to helping innovate new business models for the sector.

The 2024 World Manufacturing Report addresses various tipping points that manufacturing companies and governments will encounter over the next five years. A "tipping point" is a critical threshold or point of no return which, when crossed, leads to large, accelerating and often irreversible changes in industry, society, and the environment. Focusing on the upcoming "positive" and "negative" tipping points for the manufacturing sector leading up to 2030, such as climate change, technological shifts, talent shortages, or new geopolitical realities, the 2024 World Manufacturing Report ambitions to provide a strategic framework for global policy experts and industrial leaders to futureproof manufacturing companies and their supply chains in the face of a foreseen volatile, uncertain, complex, and ambiguous business environment in the forthcoming years.

By embracing technological advancements, fostering innovation, and solid multi-stakeholder partnerships, the 2024 World Manufacturing Report encourages the creation of a shared vision for how the manufacturing sector could evolve towards competitive industrial development models that align with the new sustainable manufacturing blueprints for an economically, socially, and environmentally prosperous future.

Project Methodology

The World Manufacturing Report is an annual whitepaper discussing critical trends in the manufacturing sector. This year, the focus has been on "New Perspectives for the Future of Manufacturing," examining the (geo) political, economic, social, technological, legal, and environmental trends shaping global manufacturing with an Outlook towards 2030.

The 2024 World Manufacturing Report was developed by a heterogeneous Editorial Team in terms of gender and country and supported by an International Advisory Board composed of people from prestigious universities and organisations. The Report was built upon integrating scientific and grey literature sources through an extensive review of the state-of-the-art and practice. This process led to analysing the main tipping points for the manufacturing sector as it heads towards 2030 and providing recommended actions to face them.

Finally, as for the past four years (2020-2023), the 2024 World Manufacturing Report has included a set of case studies written by Young Manufacturing Leaders. These were selected as winners from among the Young Manufacturing Leaders participants in a dedicated call for papers. The Young Manufacturing Leaders project, co-funded by the European Union under the EIT Manufacturing Initiative, is a global network of students and young workers interested in a career in the manufacturing sector.

1

New perspectives for the future of manufacturing

Outlook 2030

Outlook 2030: "A strategic foresight exercise based on future manufacturing scenarios where positive or negative tipping points are reached, and actions can be planned upfront to leverage these upbeat impetuses or avoid those thumbs-down momentums."

A manufacturing outlook is a strategic planning exercise that involves analysing and forecasting future scenarios based on trends, challenges, and opportunities that could positively or negatively impact the global manufacturing sector. The 2024 World Manufacturing Report presents a unique Outlook 2030 for the global manufacturing sector. It helps manufacturers worldwide anticipate positive and negative tipping points for their industries based on the potential geopolitical, economic, social, technological, legal, and environmental forces that may create them.

By combining positive and negative manufacturing tipping points and future scenarios, the 2024 World Manufacturing Report offers insights for manufacturers to better prepare for plausible significant changes in the global manufacturing landscape, ensuring they remain competitive and resilient in a volatile, uncertain, complex, and ambiguous (VUCA) environment.

Driving forces shaping the future of manufacturing towards 2030

Driving Force: "A force that propels or inhibits manufacturing innovation, automation, and sustainability to meet future global demands."

Geopolitical driving forces

Political stability and international cooperation can create a favourable environment for manufacturing sector growth, with trade agreements, infrastructure investments, and government incentives stimulating industrial expansion and technological advancement. Geopolitical collaborations, such as those aimed at climate action, can drive the adoption of sustainable practices, opening up new global markets and reducing operational risks through international standards. However, geopolitical tensions and protectionist policies can disrupt supply chains, increase costs, and create uncertainty for all manufacturers. Trade wars, sanctions, and political instability in key regions can lead to supply shortages and higher tariffs, making it difficult for manufacturers to plan and invest. Additionally, shifting regulatory landscapes across different countries can create compliance challenges, requiring manufacturers to constantly adapt to new legal requirements and standards.

Economic driving forces

A robust global economy supports growth in manufacturing industries through increased demand, investment in new technologies, and expanding production capacity. Economic development in emerging markets can open new avenues for investment and create larger consumer bases for manufactured goods. Access to capital markets and favourable interest rates also facilitate expansion and innovation. However, economic downturns, inflation, and fluctuating currency exchange rates can negatively impact manufacturing. Recessions can decrease demand, forcing manufacturing companies to downsize or delay investments. Rising material and labour costs and global supply chain disruptions can squeeze profit margins and make it difficult for manufacturers to remain competitive. Economic inequality can also impact consumer spending patterns, affecting demand for specific products.

Social driving forces

Social trends, such as the growing demand for mass-customised or personalised products and the emphasis on their sustainability, can drive innovation and open up new market opportunities in manufacturing industries. Consumer preferences for ethically produced goods can lead to higher sales for manufacturing companies prioritising social responsibility. Additionally, focusing on diversity and inclusion in the workforce can lead to more creative problem-solving and improved corporate culture, enhancing productivity and employee satisfaction. On the other hand, changing social expectations can pose challenges for manufacturers. The increasing emphasis on corporate social responsibility (CSR) requires manufacturers to invest in ethical practices, which can be costly and complex. Additionally, shifts in consumer behaviours, like the move towards minimalism or digital consumption, can reduce demand for physical products. Labour shortages, driven by demographic shifts or evolving career preferences, can also create challenges in finding and retaining skilled workers.

Technological driving forces

Technological advancements, such as artificial intelligence (AI), robotics, and the Industrial Internet of Things (IIoT), are revolutionising many manufacturing industries by enhancing efficiency, reducing costs, and enabling new product innovations. These advanced technologies allow for more precise and flexible production processes, better quality control, and the ability to respond to market changes rapidly. The continued development of the Industry 4.0 paradigm will enable manufacturers to create brighter, more connected factories that can optimise production resources and reduce waste. However, the rapid pace of technological change also presents significant challenges. Adopting new technologies can be prohibitive, particularly for smaller manufacturing companies. Cybersecurity threats are also a considerable concern, as more connected systems create new vulnerabilities. Also, the reliance on complex technologies can lead to operational disruptions if systems fail or there is a need for more skilled workers to manage and maintain them. The digital divide between manufacturing regions and companies could exacerbate inequalities within the sector.

Legal driving forces

Clear and consistent legal frameworks can provide stability and predictability for manufacturers, enabling them to plan and invest confidently. Regulations that promote fair competition, protection of intellectual property, and ensure safety and environmental standards can create a level playing field and encourage innovation. Government incentives for sustainable practices and technological innovation can drive industry growth and modernisation. Yet increasingly complex and varied legal requirements across different jurisdictions can create significant challenges for global manufacturers. Compliance with environmental, safety, and labour regulations can increase operational costs and complexity. Frequent regulation changes, particularly in data protection or environmental standards, can lead to uncertainty and require costly adjustments. Non-compliance risks, including fines and reputational damage, are also significant concerns for manufacturers operating in multiple legal environments.

Environmental driving forces

Environmental forces, like the growing focus on sustainability, are driving significant innovation in the manufacturing sector. Hence, manufacturing companies that adopt eco-friendly practices can benefit from enhanced brand reputation, access to new markets, and compliance with regulatory requirements. The shift towards renewable energy and resource-efficient processes can also lead to long-term cost savings and resilience against resource scarcity. However, environmental challenges also pose significant risks. Climate change can disrupt supply chains, damage infrastructure, and create uncertainty in resource availability. Complying with increasingly stringent environmental regulations can require substantial investment in new sustainable (green) technologies and processes, which may strain resources, particularly for smaller manufacturers. Additionally, pressures to reduce environmental impact can conflict with traditional business and operating models focused on growth and profitability, requiring manufacturing companies to rethink their strategies and make difficult trade-offs.

Tipping points

Tipping point: "A moment of critical mass, a boiling point when one or more radical changes or shifts occur" — Gladwell (2000).[1]

A tipping point, in the manufacturing context, is defined as a point in time, a moment of critical mass when one or more radical changes or shifts take place in a manufacturing intra- or inter-ecosystem or part of it, so this becomes self-perpetuating beyond its threshold, leading to substantial, widespread, frequently abrupt, and often irreversible impacts to itself and surrounding environment, being these effects of a positive or negative nature.[2]

More specifically, such disrupting shifts, caused by a tipping point, in a manufacturing intra- or inter-ecosystem can trigger non-linear change processes driven by one or more system-internal feedback mechanisms. These processes inevitably lead to qualitative differences, positive or negative, in the system's state, which are often irreversible.[3]

A positive manufacturing tipping point is a critical threshold where geopolitical, economic, social, technological, legal and/or environmental forces trigger significant changes for good in manufacturing and supply chain practices, self-reinforcing progress towards more sustainable and equitable manufacturing ecosystems. These tipping points can lead to rapid and widespread transformations of the manufacturing industries, like digital and green transitions, driving systemic shifts towards sustainable industrial development. Hence, positive tipping points are crucial for accelerating the evolution of new sustainable manufacturing businesses and operating models. This can help overcome the inertia to keep or delay the status quo and address the grand manufacturing challenges many industries must soon face.[4]

Conversely, a negative manufacturing tipping point is a predominant detrimental event or momentum in time where geopolitical, economic, social, technological, legal, and/or environmental forces trigger negative shifts or cause damaging impacts to positive manufacturing and supply chain practices. These forces switch manufacturing ecosystems into an undesired system state, causing degradation to their performance and surrounding environment. These undesired tipping points can quickly lead to cascading adverse events that ultimately destabilise and threaten the global manufacturing sector's economic, environmental, and social sustainability.[5]

Types of positive and negative tipping points

Geopolitical tipping points

In the global manufacturing context, a geopolitical tipping point is a critical juncture in international trade relations or global political relations that has the potential to significantly alter, positively or negatively, the structure, functioning, or stability of worldwide manufacturing and supply networks. These tipping points can lead to significant changes, for better or worse, in how and where goods are produced, sourced, and traded, causing reconfigurations in global supply chains and manufacturing hubs and impacts in their markets, shifting the global manufacturing dynamics.

Positive geopolitical tipping points refer to significant events or developments that reshape the global manufacturing landscape, leading to favourable happenings. These events, such as the signature of international trade agreements or regional economic integration efforts, enable positive outcomes for the manufacturing sector, for example, enhanced economic growth for industries, development of emerging markets, increased international trade cooperation, manufacturing (and logistics) innovation, and resilience in global supply chains. These positive tipping points aim for a more stable and diversified global economy with economic development opportunities for all markets, from emerging to developed, increased international trade, and advanced sustainable manufacturing and supply chain practices.

Alternatively, negative geopolitical tipping points are critical incidents that disrupt the global manufacturing landscape. These adverse events include trade wars, protectionism, export restrictions, and regulatory fragmentation, to mention a few that disturb or even interrupt international trade and global supply chain operations. Their cascading effects can negatively impact the global manufacturing sector, for instance, starting with increased production costs and reduced international trade efficiency, followed by shortages of raw materials and closure of supply routes, up to the extreme need to relocate production facilities.

Economic tipping points

In the global manufacturing landscape, an economic tipping point refers to a critical threshold where a significant, positive or negative change or shift occurs in the economic conditions that determine a market's manufacturing and consumption patterns. These tipping points can lead to new business and operating models, emerging industrial leaders, evolving market dynamics, or fresh sources of competitive advantage after the economic alterations have passed, with some being winners or losers because of these economic changes.

Consequently, positive economic tipping points refer to critical moments where a favourable transformative change occurs in the economy, leading to widespread benefits for the manufacturing sector and society. Examples of these moments include the achievement of economies of scale in novel manufacturing paradigms such as green manufacturing, lowering the marginal costs of production of green products, and leading to increased investment, job creation, and sustainable economic growth in green industries, or shifts to new economic models like the circular economy that can reduce the need for virgin raw materials and minimise waste, lowering overall production costs and creating new revenue streams from repairs, refurbishment, remanufacturing, and recycling activities. Overall, these positive tipping points enhance productivity, reduce production costs, and create new growth opportunities for manufacturers.

Conversely, negative economic tipping points imply critical events where economic changes adversely affect manufacturing industries and their markets. Some instances that could cause a negative economic tipping point are trade wars, labour shortages, resource scarcity, and financial crises. These types of tipping points, first of all, can be connected to other kinds of tipping points, such as geopolitical and social ones and can have profound effects leading to reduced economic growth, a slowdown in global trade, higher unemployment rates, the rise of production resource prices, and delays in investments.

Social tipping points

In worldwide manufacturing, a social tipping point means a profound, positive or negative moment when cumulative social pressures or societal factors like labour movements, or even sometimes new labour regulations, reach a point that causes a significant change or shift, for better or worse, in manufacturing practices related to labour standards and working conditions. In their positive type, these tipping points advocate for more socially responsible manufacturing industries offering fair wages, safe and healthy working conditions, respectful treatment of all employees, and engagement with the local communities that surround them to nurture positive relationships.

On the one hand, positive social tipping points describe a severe moment when societal pressures create beneficial changes for the workforce, ensuring notable improvements in workers' quality of personal and professional life. These joyous moments include adopting fair labour standards, including health and safety, strengthening workers' rights and unions, investing in workers' training and development, promoting gender equality and diversity, creating more inclusive workplaces, and improving work-life balance initiatives. By focusing on making these positive moments happen, manufacturing industries can create more supportive work environments and engage their workforces in their jobs, leading to increased productivity.

On the other hand, negative social tipping points relate to a critical time when societal pressures, sometimes combined with economic and technological pressures (tipping points), lead to harmful or destabilising shifts in the labour market and working conditions, severely affecting workers' employment rates, wages, safety standards, and overall physical and mental wellbeing. Patterns of these negative tipping points include discrimination and inequality in labour practices, evasion of safety and occupational health regulations, labour exploitation, and even unjustified job displacements due to automation and robotics.

Addressing these social issues will require a strong focus on labour rights, protections, and equitable practices to ensure that workers are not left behind as industries evolve or are pressured.

Technological tipping points

In international manufacturing, a technological tipping point indicates a point in time when a specific technology or set of technologies reaches or fails to reach a level of maturity, affordability, and adoption that causes a dramatic shift in global manufacturing and supply chain practices, like the case of the new Industry 4.0 technologies that have given birth to the digital and smart manufacturing paradigms, or the case of the artificial intelligence winters when this technology has stagnated before reaching its plateau of productivity. These shifts include widespread changes in how products are designed, engineered, manufactured, and delivered and how processes are executed and controlled. Moreover, reaching a technological tipping point often triggers other changes (or tipping points), including shifts in competitive dynamics, business and operating models, nature of work, and supply chain configurations.

Accordingly, positive technological tipping points denote a moment when a new technology or set of technologies leads to significant improvements in products and production efficiency, quality, and sustainability. These tipping points can create economic, environmental, and social benefits for manufacturers. Examples include additive manufacturing (also known as '3D printing') technologies that have allowed for rapid prototyping, customisation, and on-demand (low- and mid-volume) production with beneficial triple-bottom-line outcomes by reducing material waste, energy consumption, and environmental impact (footprint) in contrast to subtractive manufacturing processes, offering more design freedom, hence, leveraging human creativity, and opening up new possibilities for novel production and supply chain models such as distributed manufacturing; advanced (collaborative) robotics and (smart) automation technologies that have improved production precision and speed, offering higher productivity levels and better quality controls, and removed workers from dull, dirty, and dangerous tasks in manufacturing processes; or digital-twin technologies (including their set of related technologies such as the Industrial Internet of Things (IIoT) and machine learning) that have led to significant improvements in manufacturing efficiency thanks to their real-time process monitoring, analysis, and optimisation.

Conversely, negative technological tipping points can occur when a new technology or set of technologies recognise that they have failed to deliver their promised value and, therefore, the possibility of return on investment or when their delivered benefits are outweighed by their utilisation risks. For instance, cybersecurity threats if proper cybersecurity frameworks are not implemented before connecting any IIoT device, equipment, or system to the enterprise industrial network. Furthermore, it is also possible to consider other hybrid negative socio-technological tipping points like an overreliance on automation or lack of digital skills in the workforce that have led to big failures in adopting new technologies with significant setbacks in the digital transformation journey of a manufacturer. Thus, careful consideration and management of technological changes are advised to mitigate their negative tipping points.

Legal tipping points

Within a global manufacturing environment, a legal tipping point refers to a critical moment when an international (or national) regulation, law, policy, standard, or agreement changes, for better or worse, with significant, positive or negative impacts on the way manufacturing industries operate and conduct their businesses. Consequently, these tipping points drive substantial changes in industry practices (including trade), investment decisions, and competitive dynamics. Moreover, legal tipping points are sometimes related to one or more of the already-mentioned or to-be-mentioned tipping points.

In critical times, positive legal tipping points convey new legal or regulatory developments that drive significant beneficial changes for the manufacturing sector, customers, and society. These changes can incentivise sustainability and innovation with regulations promoting, for instance, the green manufacturing paradigm or the digital and smart manufacturing paradigms, or trade liberalisation through free trade agreements and the harmonisation of international industry standards, including labour rights and intellectual property (IP) protection, that can enhance global supply chain efficiency, allowing manufacturers to compete more effectively, to some extent, in the worldwide marketplace.

Then, negative legal tipping points can occur when overly cautious legal frameworks overregulate, for example, emerging technologies such as artificial intelligence or inadequate enforcement of environmental, trade, IP, or labour regulations, leading to a loss of competitiveness for everyone.

Environmental tipping points

In the ecosphere of manufacturing, an environmental tipping point defines a critical threshold, positive or negative, beyond which the ecological impacts of manufacturing processes, including their supply chains, become irreversibly damaging for the planet or may start allowing for its recovery for good. The environmental tipping points are the most well-known type addressed in this Report but have negative connotations, with the climate change crisis being the most representative. Nevertheless, their positive and negative inferences are explored to address mitigation and regeneration actions needed to save our planet, such as the green manufacturing paradigm or the emerging circular and regenerative manufacturing paradigms.

As a result, positive environmental tipping points refer to pivotal changes or shifts in manufacturing and supply chain practices where at least net-zero, but hopefully net-positive, operations are achieved, stopping the detrimental impact of the sector and its industries on our planet and starting its regeneration with the help of the widespread adoption of green technologies, circular business models, sustainable materials, and carbon-neutral manufacturing processes in a first instance, immediately followed by the vision of the so-called regenerative manufacturing systems that aim to put more back into society and the environment than they take out, to compensate for the harm of past industrial systems.

Lastly, negative environmental tipping points highlight the critical thresholds beyond which the environmental impacts of manufacturing and supply chain operations become so severe that they cause irreversible damage to the ecosphere of the sector and society and whose cascading adverse effects are so complex, if not impossible, to reverse. Infamous examples it is hoped will be avoided are climate catastrophe, critical resource exhaustion (like rare earth materials, fundamental for technology development), pollution overload, and waste management failure. Avoiding these negative environmental tipping points is crucial for ensuring the long-term ecological sustainability of the global manufacturing sector.

Beyond 2030: four scenarios for the future of manufacturing

In considering the future of manufacturing beyond 2030, 'scenarios' serve as valuable tools for strategic foresight exercises. These can help manufacturers envision, plan for, and increase their chances to thrive in inconceivable future competitive arenas. They represent different, plausible competitive paths for the sector, whether shaped by technological advancements, regulatory changes, or shifts in global trade dynamics. Thus, scenario planning encourages diverse thinking and inspires creative strategy development to defend a competitive edge or develop new competitive advantages. The following four scenarios for the future of manufacturing are not predictions but imaginative explorations or narrative views of various possible futures beyond 2030 for the global manufacturing sector.

Their aim is not to endorse a specific direction but to provide a framework for discussion, enabling decision-makers to anticipate grand challenges better, seize opportunities, and craft resilient strategies for an evolving manufacturing landscape.

Green transformation as a growth engine for the future of manufacturing

Scenario 1: "Redefinition of growth by integrating circular economy principles and embracing emerging green markets while always striving for a net positive impact."

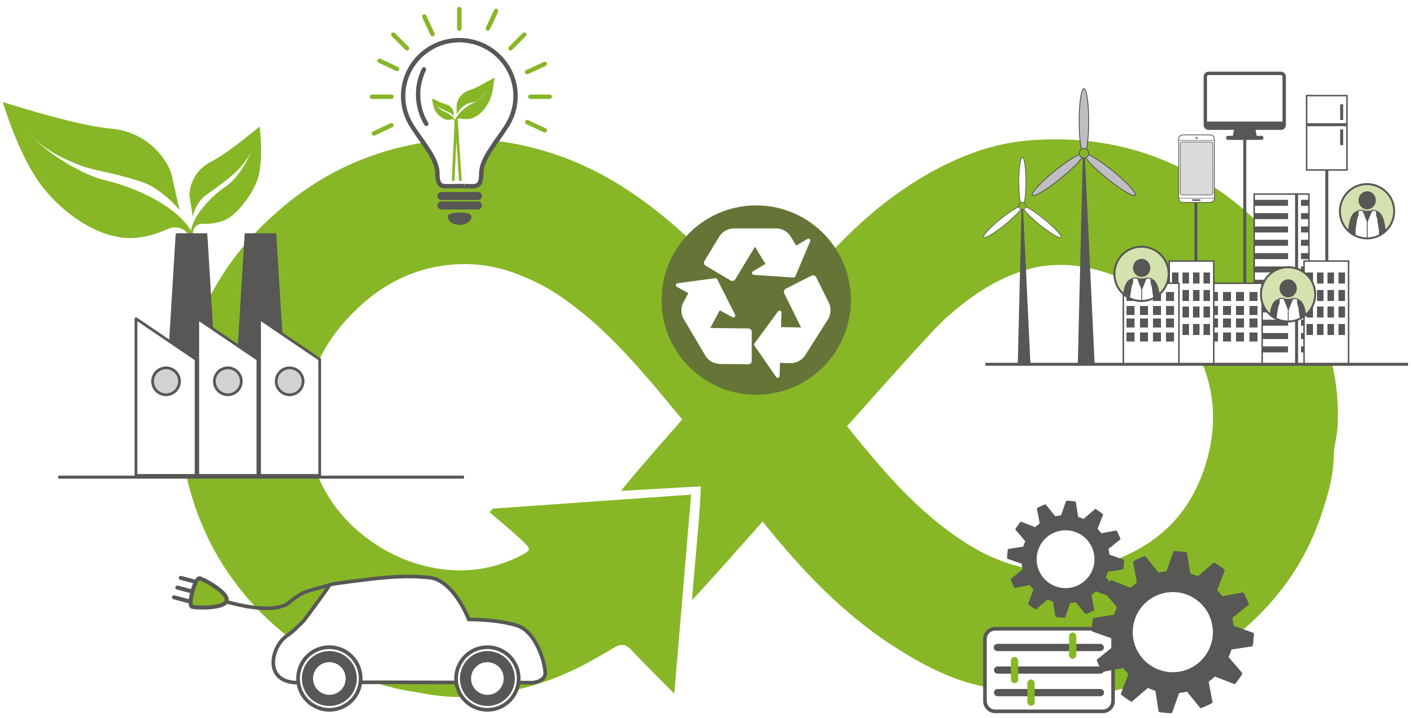


Figure 1

"Green transformation as a growth engine" scenario

In this transformative scenario, manufacturing industries worldwide experience a profound shift towards sustainability, driven by robust regulatory frameworks, evolving consumer preferences, and strategic investment in green technologies. Manufacturers fundamentally alter their business and operating models to integrate circular economy principles, which emphasise designing products for durability, repairability, and recyclability. Hence, this shift goes beyond incremental changes, aiming for a systemic transformation that reduces environmental impacts.

In contrast to enhancing manufacturing efficiency, sustainable manufacturing could also be regarded as a core value. By 2030, sustainability will become the cornerstone of manufacturing industries, not merely as a compliance requirement but as a core value embedded in every facet of operations. This shift is driven by growing (green) consumer demand for environmentally responsible products, stricter regulations, and the increasing awareness of the impact of manufacturing. In this scenario, manufacturers prioritise sustainability from the initial design phase to the end of their product's lifecycle. Eco-design principles guide the creation of durable, energy-efficient products designed for disassembly, repair, and recycling. Raw materials are chosen based on their environmental footprint, with a strong preference for renewable, recycled, or bio-based resources. The adoption of circular economy practices is central to sustainable manufacturing. Waste is minimised through closed-loop systems where by-products and end-of-life products are reused and recycled into production processes. Manufacturing companies develop innovative methods to reclaim and repurpose materials, significantly reducing the need for virgin resources and decreasing overall waste.

Manufacturers adopt practices like material recycling, product take-back schemes, and renewable energy integration. Additionally, they invest in energy-efficient production technologies and renewable energy sources to reduce their carbon footprint. However, the effectiveness of these sustainable practices must be carefully evaluated to avoid the pitfalls of greenwashing. Independent verification and transparent reporting are essential to prove that sustainability efforts result in tangible environmental benefits.

Table 1

"Green transformation as a growth engine" scenario PESTLE analysis

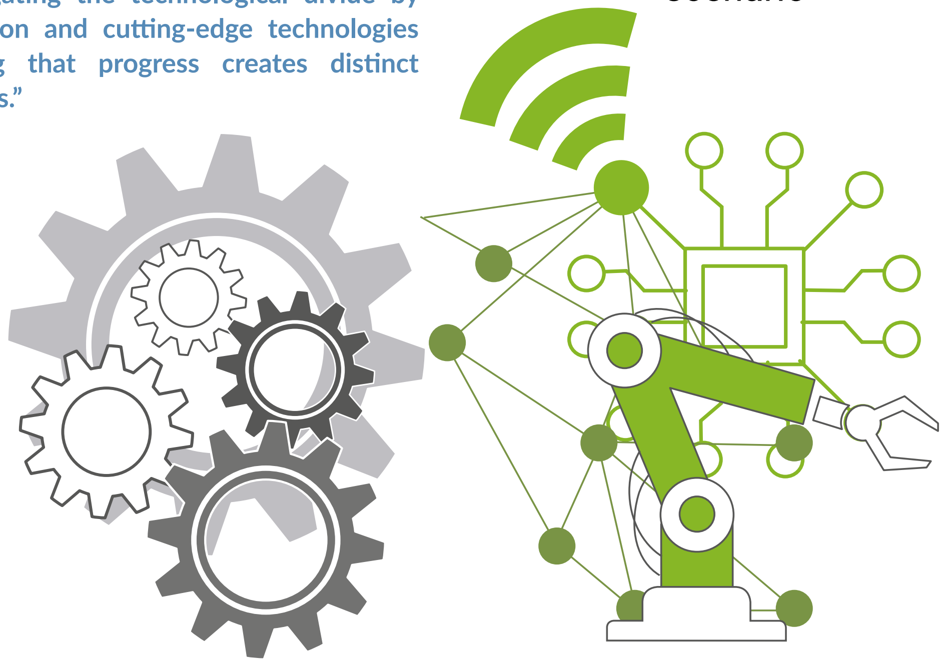
PESTLE dimension	Green transformation as a growth engine
Political	• Supportive regulatory environment with incentives for sustainable (green) practices and penalties for non-compliance.
Economic	• Long-term cost benefits from resource efficiency and reduced waste. • Creation of new market opportunities, such as green lead markets.
Social	• Increased consumer demand for truly sustainable products and practices. • Heightened expectations for corporate responsibility and transparency.
Technological	• Investment in advanced (green) technologies for energy efficiency and product sustainability. • New green markets like renewables, water supply, or hydrogen. • Ongoing innovations in circular economy practices.
Legal	• Strict regulations requiring transparent reporting and proof of environmental impact. • Emphasis on avoiding greenwashing.
Environmental	• Significant reduction in waste and resource use if practices are effectively implemented. • Potential for positive environmental impact from new green technologies.

Technological divergence in the future of manufacturing

Scenario 2: "Navigating the technological divide by advancing innovation and cutting-edge technologies and understanding that progress creates distinct leaders and laggards."

Figure 2

"Technological divergence" scenario



In this scenario, technological advancements create a divided manufacturing landscape. Manufacturing regions and companies with access to cutting-edge technologies such as AI, IoT, and robotics gain a significant competitive advantage over those that lag.

Research on artificial intelligence and data science leads to the trends that manufacturing is heading for a development that could be subsumed in "digital first". Manufacturing is instead seen as a domain for applying industrial artificial intelligence and data analytics. In this scenario, data becomes the most valuable resource in manufacturing, with AI leading every aspect of production, from product design and development to manufacturing to logistics and customer service. AI is at the core of all production operations. Advanced AI systems manage and optimise production lines with minimal human intervention, making real-time decisions. These AI systems analyse vast amounts of data from sensors embedded in machinery, production lines, and supply chains, predicting potential issues before they occur and automatically adjusting processes to maintain optimal performance. Product design is revolutionised by data analytics, with AI systems capable of processing consumer preferences, market trends, and performance data to create innovative and perfectly tailored designs to consumer needs. This data-driven approach enables mass-customisation, where products can be personalised at scale without sacrificing production efficiency or increasing costs. Manufacturers use AI to simulate and optimise product designs before they reach the production stage, reducing the time and cost associated with prototyping.

Table 2

"Technological Divergence" scenario PESTLE analysis

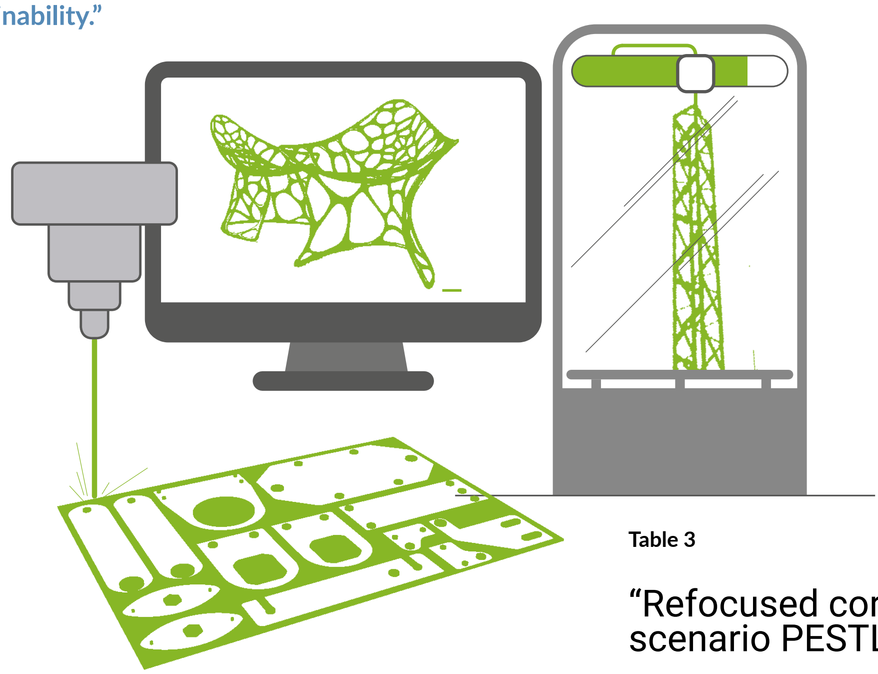
PESTLE dimension	Technological divergence
Political	• Varied national policies impacting technology adoption. • Potential for technology-driven trade policies.
Economic	• Economic disparities between tech-advanced and tech-lagging regions. • A competitive advantage for technology leaders.
Social	• Increased inequality in employment opportunities and wages based on technological capability. • Shifting job markets.
Technological	• Rapid advancements in IIoT, robotics, and AI in leading regions. • Slower technological progress in others.
Legal	• Diverse intellectual property regulations and standards. • Varying legal frameworks affecting technology use.
Environmental	• The potential for either reduced or increased environmental impacts depends on the efficiency and sustainability of technologies.

Refocused core capabilities in the future of manufacturing

Scenario 3: "Elevation of manufacturing by harnessing breakthroughs in natural sciences – refinement of material science and advanced manufacturing processes to drive superior product performance and sustainability."

Figure 3

"Refocused core capabilities" scenario



After several years of AI and data science leading the conversation, core competencies of manufacturing take over again. The manufacturing sector enhances core capabilities such as materials science, process engineering, and advanced manufacturing techniques. Developments in materials science, such as nanomaterials or bio-inspired materials, could drive this trend. Hence, by 2030, the manufacturing sector could experience a renaissance of traditional manufacturing methods and a renewed focus on materials science. This scenario emerges as a response to the limitations and challenges faced by overly automated and digitised production environments and the growing need for sustainability and innovation in materials. Potentially, there could be a resurgence in demand for functional products that embody superior quality and durability, with industries that once relied heavily on mass production shifting towards low-volume, high-quality manufacturing processes.

Researchers and engineers focus on developing new alloys, composites, and bio-inspired materials that are not only stronger and lighter but also more environmentally friendly, such as being entirely degradable. In this scenario, developing smart materials that adapt to environmental conditions or have self-healing properties enables an enhanced lifespan, biocompatibility and performance, and reduced waste.

Table 3

"Refocused core capabilities" scenario PESTLE analysis

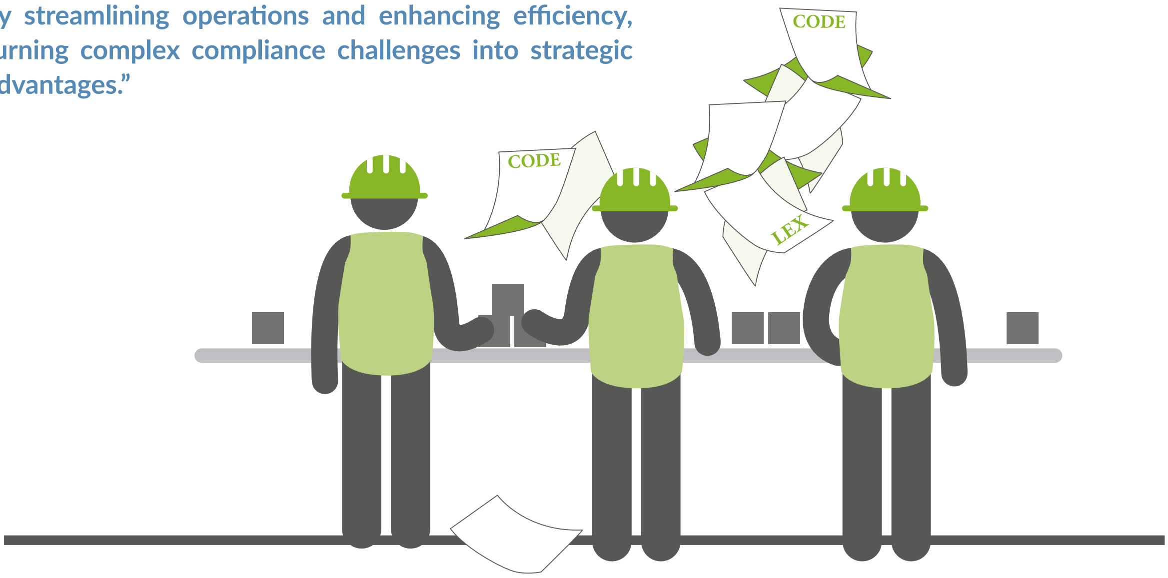
PESTLE dimension	Refocused core capabilities
Political	• Supportive policies encouraging R&D in core manufacturing capabilities. • Potential for government funding and incentives.
Economic	• Potential for higher-value products and market differentiation. • Initial investment costs in R&D and technology.
Social	• Creating high-skilled jobs and new career opportunities in materials science and advanced manufacturing. • Impact on workforce skill requirements.
Technological	• Advances in materials science, process engineering, and manufacturing technologies. • Innovation in product design and production techniques.
Legal	• Intellectual property considerations and patent regulations. • Compliance with new standards for advanced materials and processes.
Environmental	• Improved environmental performance of products due to enhanced materials. • Potential for reduced resource use and waste through advanced manufacturing processes.

Regulatory fragmentation and efficiency focus on the future of manufacturing

Scenario 4: "Adaptation to regulatory fragmentation by streamlining operations and enhancing efficiency, turning complex compliance challenges into strategic advantages."

Figure 4

"Regulatory fragmentation and efficiency focus" scenario



In this scenario, manufacturers face challenges due to regulatory fragmentation and inefficiencies arising from inconsistent regulations and market barriers. This fragmentation increases operational costs and complicates cross-border operations. Manufacturing companies must navigate different regions' diverse environmental and safety regulations, leading to higher compliance costs and operational complexity. Manufacturers focus on improving internal efficiencies and developing adaptable compliance strategies to counter these inefficiencies. Hence, by 2030, the manufacturing sector will be characterised by a relentless focus on efficiency.

This scenario emerges from increasing global competition, resource scarcity, and the need to reduce environmental impact. Manufacturers prioritise streamlined operations, waste reduction, and optimal resource utilisation, leading to a lean and highly efficient production environment. Efficiency-driven manufacturing also influences product design. Products are engineered for easy manufacturing, using fewer components and materials without compromising quality. This scenario results in faster production cycles, lower costs, and a reduced environmental footprint, making efficiency the critical competitive advantage in the future manufacturing sector.

Table 4

"Regulatory fragmentation and efficiency focus"scenario PESTLE analysis

PESTLE dimension	Regulatory fragmentation and efficiency focus
Political	• Inconsistent national regulations affecting global operations. • Need for adaptive strategies and potential for regulatory alignment efforts.
Economic	• Increased costs due to regulatory compliance and market barriers. • Focus on internal efficiencies to mitigate impact. • Challenges in achieving economies of scale and global integration.
Social	• Uneven market access and job creation across regions. • Impact on global trade and employment practices. • Potential improvements in workforce efficiency.
Technological	• Need for adaptable systems and technologies to manage regulatory compliance. • Innovation in compliance management and operational efficiency.
Legal	• Complex legal requirements across regions. • Focus on developing robust compliance strategies. • Managing legal risks.
Environmental	• Varied environmental standards affecting manufacturing practices. • Potential for improved efficiency in response to regulatory fragmentation.

2

Tipping points for the global manufacturing sector

Geopolitical tipping points

The global manufacturing sector is increasingly characterised by geopolitical developments that create radical shifts, tensions, and market uncertainty. Manufacturing companies must mitigate the risks posed by geopolitical tipping points and, as significantly, capitalise on the opportunities they create.

Trade wars

Trade wars are at a crossroads regarding globalisation's future, suggesting that they could reverse the trend towards open markets and free trade that has characterised the global economy for decades.

The ongoing trade wars represent a significant shift in global economic dynamics. In recent years, various trade wars have overlapped simultaneously, which can positively and negatively impact the manufacturing sector.

Trade wars can have adverse effects, such as increasing costs and inducing inflation, causing marketplace shortages, reducing choice, and discouraging trade. On the other hand, trade wars can have positive effects, such as increasing demand for domestic products, protecting domestic manufacturing companies from unfair competition, and promoting local job growth.[6]

There is the ongoing trade war between the US and China, the recent trade war between the European Union (EU) and China, and Western sanctions against Russia. These developments restrict trade and increase traffic between the affected regions. On the other hand, the non-affected regions reduce tariffs, and new free trade agreements are signed.[7]

Trade wars are not new; they have historical precedents dating back centuries. However, after World War II, an era of globalisation and free trade eased many trade barriers. This trend was reversed after 2018. The US triggered a trade war against China to reduce the bilateral trade deficit and stop Chinese companies' subjective unfair trade practices, such as violations of intellectual property rights and forced technology transfer.[8] Initially framed as a battle against unfair economic practices, the trade war has since morphed into a more complex geopolitical struggle. The Biden administration has largely continued the policies, emphasising a competitive stance against China. This includes tariffs and restrictions on high-tech exports and investments, reflecting a growing concern over national security and technological dominance. The economic ramifications of the trade war are profound and multifaceted. Tariffs have led to increased costs for consumers and businesses in both countries.[9] The implications of a trade war extend beyond the US and China. It has created ripples throughout the global economy, affecting countries that are part of the supply chain and those reliant on exports to these two economic giants. Trade wars will hurt the whole world's manufacturing employment.[10] For example, Southeast Asian nations have seen shifts in trade patterns as companies relocate production to avoid tariffs.

Similarly, the trading relationship between the EU and China has become increasingly contentious.[11] This conflict is characterised by tariffs, investigations, and retaliatory measures significantly affecting economies and the broader global market. Historically, the EU and China have maintained a complex trading relationship. The European Union is one of China's largest trading partners, with a significant trade deficit favouring China. In 2022, the EU's trade deficit in goods with China was nearly €300 billion, prompting calls within the EU to address perceived imbalances and unfair trade practices. The EU has accused China of dumping products below market value and providing unfair subsidies to its industries, leading to investigations into various sectors, including steel, electric vehicles, and luxury goods. Recently, the EU imposed tariffs of up to 37.6% on Chinese electric vehicles (EVs). This action responded to concerns that Chinese EVs were sold at artificially low prices, undermining European manufacturers.[12] China quickly retaliated, threatening to impose tariffs on European agricultural products, particularly pork and dairy, which are significant exports for several EU member states, including Spain and Ireland. The economic ramifications of this trade war are profound. The tariffs on Chinese goods for the EU protect local industries and encourage fair competition. European manufacturing companies that rely on Chinese components may face higher production costs, which could ultimately lead to increased prices for consumers. The EU-China trade war is a complex and evolving issue that poses significant challenges for both regions. As tariffs and retaliatory measures escalate, the potential for economic disruption increases, affecting consumers and businesses alike. On this tipping point, the outcome of this conflict will not only shape the future of EU-China relations but also have far-reaching implications for the global economy. Both sides must navigate these tensions carefully to avoid a protracted conflict that could reshape international trade dynamics and economic alliances in the near future.

In addition to the two trade wars mentioned, the impact of EU sanctions on Russia, particularly in the manufacturing sector, has been significant and multifaceted since their implementation in February 2022. The EU has imposed extensive sanctions, including export bans on critical goods and technologies, which have affected approximately one-third of the total value of Russian imports. Key sectors impacted include transport equipment, chemicals, electronics, and machinery, with transport equipment alone accounting for over 45% of the total banned products.[13] The sanctions have led to a notable decline in production across several sectors. For instance, the automotive industry experienced a dramatic collapse, with car production dropping by nearly 90% immediately after the invasion. As of early 2023, production levels were still less than 25% of pre-invasion figures, with most Western manufacturers exiting the Russian market.[14] Similar declines were observed in electronics, machinery, and other high-tech sectors, where the absence of foreign components severely hampered production capabilities. Despite these declines, overall manufacturing output in Russia has not decreased as dramatically as expected. By early 2023, manufacturing output was down only 1.7% year-on-year, indicating that specific sectors have suffered. In response to the sanctions, Russia has sought to adapt by increasing imports from non-sanctioning countries, which have filled some gaps left by the EU's restrictions. Countries such as Turkey, Kazakhstan, and Armenia have become significant trade partners, facilitating the re-routing of goods into Russia. For example, imports of mobile phones and computers from these countries surged as Russian manufacturers sought alternatives to banned Western products.[15] The EU sanctions have profoundly affected Russian manufacturing, leading to significant declines in specific sectors and prompting trade pattern adaptations. The immediate consequences have been severe. However, Russia's ability to maintain some level of manufacturing output through alternative trade routes suggests a complex and evolving economic landscape. The long-term implications of these sanctions is likely to continue to shape the future of Russian manufacturing and its overall economic resilience.[16] Their share of global trade in developing countries has increased, rising from about 22% in 1964 to approximately 44% by 2023[17] (see Figure 5).

Several factors, including tariff liberalisation and integrating national economies into global value chains, have driven this growth. Developing economies, particularly in Asia, have become key players in international trade, benefiting from their ability to produce and export manufactured goods at competitive prices.[19] While tariffs have decreased globally, the rise of non-tariff measures (NTMs), such as quotas and stringent safety standards, poses new barriers to trade. NTMs are policy measures, other than ordinary customs tariffs, which can economically affect international trade in goods, changing quantities traded, prices, or both. These measures disproportionately affect developing countries;[20] while tariffs have fallen, non-tariff measures have risen, creating new trade challenges for developing countries.[21]

Economic decoupling

Decoupling can reduce trade volumes and product affordability, increase tariffs and investment restrictions from international markets, and create a market crisis.[22]

Rapid globalisation has created interdependencies, vulnerabilities and power imbalances across economies. This can pressure supply chain nodes, creating a 'decoupling'[23] or complete economic disentanglement between economies. An example of this is the rivalry between China and the US (who account for 40% of global GDP), where both nations leverage technological dependencies to vie for geopolitical dominance and improved national security, marking a significant shift away from the international norms of free trade and open borders. As a result, interdependence has accelerated economic decoupling, with the COVID-19 pandemic further driving countries to prioritise economic self-reliance and resilience. China is the US's primary trading partner, holding approximately US$860 billion in debt (as of January 2023)[24]. Recently, this has shifted the US's

Figure 5

Trade share of developing countries on par with developed countries[18]

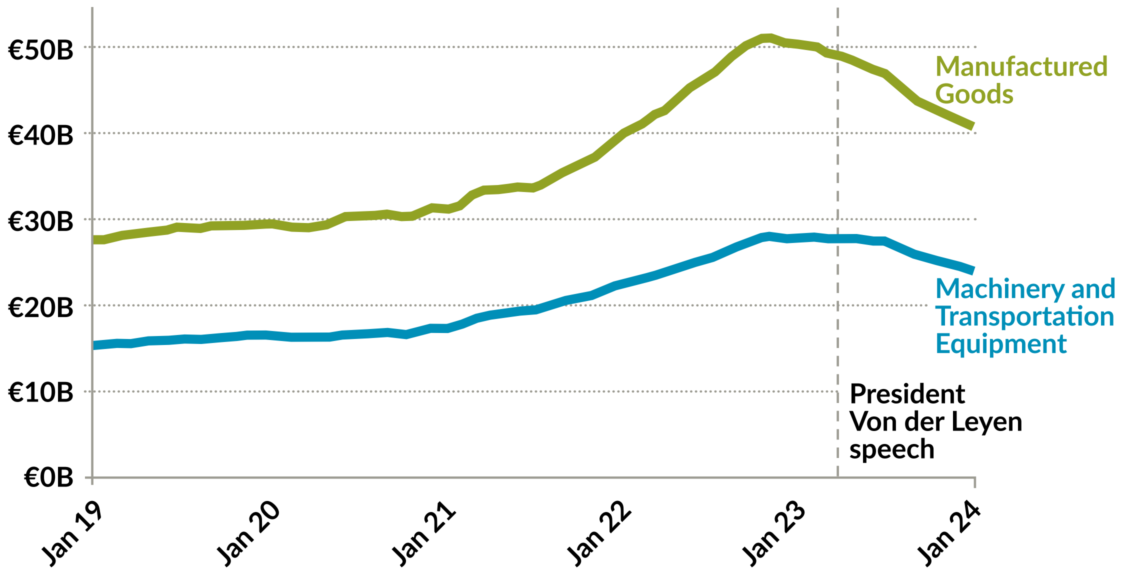
focus from decoupling to de-risking, where strategies are based on proactively recognising threats. A hard decoupling from China could prove costly and nearly impossible[25], directly affecting SMEs in the US and low-income countries, lowering global GDP by 1% and doubling the GDP in China. In her speech on EU-China relations, European Commission President Ursula von der Leyen[26] explained that diplomatic and economic de-risking was crucial to maintaining future trade relationships with China. A softer approach to decoupling will entail understanding risks related to the shift in China's financial priorities and a critical view of the EU's vulnerabilities and dependencies.

The EU's imports of manufactured goods, machinery, and transportation equipment from China are reducing (see Figure 6). However, much work remains to reduce its dependence on future clean energy technologies and EVs.

Figure 6

EU Imports of goods from China[27]

(Source: Eurostat, GeoEconomics Center Calculations)



Economic decoupling can also 'split the global market into competing technospheres'.[28] Technological leadership will then become the focus of geopolitical competition, disrupting technological ecosystems and limiting collaboration and knowledge-sharing activities between nations.

On the flipside, however, the economic decoupling between the US and China has benefited emerging countries.[29] For instance, global diversification of critical supply chains has increased foreign investments for setting up semiconductor manufacturing hubs in Malaysia, with US$13.5 billion invested in 2023. China has also begun its diversification strategy by establishing businesses in Mexico, Eastern Europe and Latin America. China made a US$1 billion investment with Canada to mine Argentina's lithium reserves and increase the country's monopoly on critical raw materials to manufacture green technologies.

Geographically advantaged countries that possess a skilled workforce, invest in upskilling and have abundant reserves of critical raw materials are likely to attract global financial investments. These nations stand to emerge as economic leaders if they can leverage these strengths as safeguards against potential economic risks from future decoupling scenarios.

Cyberattacks

The manufacturing sector is experiencing a rapid rise in cyberattacks, driven by increasing digitalisation and the integration of advanced technologies.

Cyberattacks on manufacturing companies have become a more substantial risk, and the overall cost of security measures has recently increased significantly. A tipping point towards a permanent disadvantage is imminent.

Recent reports indicate that nearly 40% of manufacturers encounter cyber incidents annually, with ransomware attacks on industrial infrastructure almost doubling in 2022. Notably, 70% of surveyed companies that suffered ransomware attacks were in manufacturing.[30]

SMEs are especially vulnerable to cyberattacks due to smaller security budgets. Still, large manufacturing companies are more attractive to targeted attacks due to the higher amount of ransom money extracted.[31]

Ransomware payments in 2023 surpassed the US$1 billion mark, the highest number ever observed.[32] As manufacturers adopt smart factory initiatives and the Internet of Things (IoT), they inadvertently expand their attack surfaces, making them prime targets for cybercriminals. Contributing factors to the heightened risk of cyberattacks in the manufacturing sector are the merging of information technology (IT) and operational technology (OT) systems, which creates vulnerabilities as both networks become interconnected, known as the IT-OT Convergence. This convergence blurs security lines, making it easier for attackers to exploit weaknesses. Other contributing factors are, for instance, legacy systems and a need for cybersecurity awareness. The consequences of these cyberattacks can be severe. Unauthorised access accounts for 87% of attacks, often leading to operational disruptions in 86% of cases. Due to ransomware attacks, 29% of the companies in the survey said they were forced to downsize and cut jobs.[33] The impact of cyberattacks on manufacturing companies extends beyond immediate financial losses. Operational disruptions can halt production lines, leading to delays in product delivery and loss of customer trust. Manufacturing companies must adopt a proactive approach to cybersecurity to combat the growing cyberattack threat. Key strategies include recurring risk assessments, employee training, robust security measures, and an incident response plan.

With the continued digitalisation of the manufacturing sector and rising global tensions, the risks associated with cyberattacks will increase further. Ransom money is individually priced for the targeted company according to financial statements. Therefore, an existential threat to manufacturing companies is not intended, but business growth and innovation are hindered dramatically in the case of a successful attack.

Resource nationalism

The geopolitical rivalry has now led to a race among superpowers such as the EU, the US, and China, which have increased subsidies, trade fragmentation, and the domestic production of green technologies to promote self-sufficiency and maintain their global market share.

Global supply chains are increasingly complex due to global supplier networks, producers and distributors. Due to this diversification, their importance has shifted from economics to geopolitics, with concerns about where materials and goods are sourced from and their relevance to national security and supply stability.[34]

Critical material supply chains are growing in relevance because of global decarbonisation regulations, the subsequent need for industrial green transitions, and advancements in technological developments due to Industry 4.0. Green transitions have been fuelled using cleaner solutions such as battery technologies and geoengineering solutions such as solar - or wind - power management. The demand for critical materials in the last five years was approximately US$320 billion and is expected to double in the next few years.[35] However, geopolitical conflicts have intensified the need for critical materials compared to traditional minerals such as iron, aluminium and copper. Increasing geopolitical competition and export restrictions by resource-intensive countries lead to global economic disruptions. These are various forms of 'resource nationalism', a term used for government involvement in the mining, processing, distributing and marketing of natural resources. It is a neutral concept and an economic initiative[36] that can offer underdeveloped countries the chance to engage in the global division of labour and the sustainable supply of critical materials. Examples of resource nationalism can be seen in countries such as Zimbabwe, Indonesia, The Philippines and Chile, which progressively ban exports of unprocessed lithium and nickel ore, favouring domestic processing of these materials. Accordingly, resource nationalism can be seen in two forms: resource sub-nationalism and resource supra-nationalism.[37] Resource sub-nationalism occurs locally, where governments in mineral-rich areas demand more outstanding shares of value, which could lead to conflict. Resource supra-nationalism, on the other hand, occurs when countries require access to globally scarce resources from resource-rich countries that are less powerful, thus leading to wars and supply chain disruptions.

Non-economic factors such as resilience and security are now prioritised over economic and other market factors. Autonomous initiatives such as the EU's Critical Raw Material Act (CRM Act)[38] have combined reshoring strategies with cooperative diversifications, and the US Inflation Reduction Act (IRA)[39] has combined reshoring and 'friend-shoring' to improve trade and industrial partnerships outside orthodox political frameworks. The EU's Green Deal has initiated decarbonisation efforts to address climate change. These 2050 net-zero targets will require a sustainable supply of critical materials. Additionally, these will weaken countries with fossil fuel reserves and strengthen countries with abundant renewable energy sources or those that can transform and distribute such sources. However, the ability of governments to adopt climate-related policies will ultimately determine their success in climate risk mitigation.

Technological sovereignty

Technological sovereignty can lead to developing and accelerating "local/national/regional" capabilities, new industries and sectors, product development, innovation, growth, and job creation.

Technological competition among nations and regions is intensifying, and the fear of falling behind in advancement has made technological sovereignty a worldwide concern. With growing geopolitical tensions, prolonged effects after the COVID-19 pandemic, increasing numbers of cyberattacks and the rise of derisking strategies, it has become a potent political theme worldwide to ensure technological sovereignty. Nations and regions increasingly recognise the importance of controlling their technological future to ensure safety, welfare, growth, and autonomy.

To be sovereign can generally be described as "having the highest power or being completely independent".[40] From a perspective of technological advancements, sovereignty can be understood as the ability to act autonomously and independently and to implement political and societal actions without being hindered by a lack of control over technology.[41] Thus, technological sovereignty involves access to technology and relevant products or components that can be secured reliably through a nation's capacity or its relations or alliance with other countries or regions.[42] Digital sovereignty, information and communication technology (ICT) sovereignty, information sovereignty, and data sovereignty have also been discussed recently. Technological sovereignty has overlapping aspects, such as controlling the data, information, technology, and ICT used in a society.[43] Within the European context, technological sovereignty is often discussed in connection to strategic autonomy and industrial autonomy – underlining the ability to act independently from other countries and regions.[44] Technological sovereignty is also a key enabler for the broader concepts of innovation and economic sovereignty.[45]

Technologies play a vital role in society, which has been especially evident after the COVID-19 pandemic. ICTs are critical not only to individuals but especially to companies, industries, and nations. Likewise, access to life-science technologies, medicine, etc., is vital to any society to ensure wellbeing. Microelectronics development, research, and production are examples of areas in Germany and Europe connected to technological sovereignty and reliable, stable, and secure access to microchips.[46] The German VDE (Association for Electrical, Electronic, and Information Technologies) emphasises the need for a broad perspective on technological sovereignty rather than limiting the focus to digital, data or media sovereignty. Thus, access to commodities, components, and knowledge is also part of technological sovereignty. Furthermore, the VDE use different fields of technology such as ICT, software, AI, automation, energy, medical technology, etc. and other application areas like automotive engineering, electronics and electrical engineering, energy supply and mechanical engineering to further elaborate on relevant aspects of technological sovereignty. The EU refers to six critical enabling technologies for Europe's technological sovereignty: advanced manufacturing, advanced nanomaterials, life-science technologies, micro-/nano-electronics and photonics, AI, and security and connectivity technologies.[47] The National Science and Technology Council has published a list of critical and emerging technologies necessary for national security in the US.[48] Accordingly, research and innovation policies are adopted to accelerate technological development and sovereignty worldwide.[49]

For manufacturing companies, developing advanced technologies, a reliable supply of critical materials and components, and stable access to critical infrastructure are necessary for long-term competitiveness. The race of countries to win technological sovereignty can be a significant tipping point for any manufacturing industry. Furthermore, manufacturing is vital for any nation or region seeking to develop, recover, or retain technological sovereignty. Technological sovereignty can be considered high if a critical technology, including the necessary knowledge, competencies, components, and infrastructure, is produced and secured within a specific nation or region. This also includes the entire value chain required for the technology.[50]

Moreover, technologies enable industrial companies to extend the range of products and services offered, expanding global trade markets and increasing global investments and corresponding returns. While increased independence, innovation, security and growth are among the potential opportunities for manufacturing companies in the technological sovereignty race, challenges remain. Among the adverse effects are reduced access globally to new and critical technologies, reduced collaboration and innovation and reduced usage and implementation of promising new technologies and digital developments.

Regulatory fragmentation

The global patchwork of AI regulation is likely to become more complex in the future.

Regulations and policies most often occur at a national or regional level. While nations and regions may decide to tackle critical global issues very differently, from climate change and global warming to AI and cybersecurity, differences in regulations can result in severe impacts on manufacturing companies. The race to develop and regulate new technologies and promote sustainability and circularity are highly relevant geopolitical themes. As a result, different regulations create a complex set of other conditions for manufacturing companies worldwide.

Regulatory fragmentation – or regulatory divergence – can be defined in various ways depending on the type of regulation in focus. Often, regulatory or financial fragmentation is discussed in connection with the global economy and monetary system, referring to the situation where multiple regulatory entities create overlapping regulations, resulting in inconsistencies, inefficiencies and unclear objectives.[51] A recent study concluded that regulatory fragmentation, redundancy, and inconsistency in the US – for instance, when multiple federal agencies oversee a single issue – increase the cost of manufacturing companies and lower productivity, profitability, and growth.[52] Furthermore, in the financial sector, regulatory divergence often refers to inconsistencies in regulation across different jurisdictions, such as competition law, product regulation, consumer protection, and product. Regulation can represent a significant burden to manufacturing companies.[53]

From a geopolitical perspective, regulatory fragmentation and diversification policymaking should generally be seen broadly and not just in terms of financial regulation. Nations and regions worldwide have different approaches to regulating and promoting critical aspects of society, security and welfare, as well as different interpretations and ways of enforcing these. Regulations[54] include competition, trade, markets, security and cybersecurity, environment, emissions, technology, and AI. For instance, cyber-related regulatory fragmentation has been defined as the situation when financial institutions must comply with different regulations in the same or other jurisdictions, which are similar, conflicting and do not enhance cybersecurity or resilience.[55]

Furthermore, diverse approaches to regulating sustainability and new technologies are geopolitically related types of fragmentation that impact manufacturing companies worldwide. Different national and regional conditions and goals broadly impact climate policies, sustainability regulations, and the adoption of reporting directives among countries. In the EU, the European Sustainability Reporting Standards (ESRS) were adopted in 2024 to be used by all companies subject to the Corporate Sustainability Reporting Directive (CSRD). This is an example of global collaboration that can decrease the probability of policy and regulatory fragmentation, leading to a higher likelihood of combatting climate change.

While governments worldwide promote the development of critical technologies to gain sovereignty, they are also tackling the issue of how to regulate new technologies best, especially AI, concerning national security.[56] Many countries have national AI policies and policies applying to specific AI uses.[57] The EU Parliament adopted the first EU regulatory framework for AI as part of the digital strategy (EU AI Act) in the Spring of 2024, while the US has released various frameworks and guidelines related to AI, including the executive order on the safe, secure and trustworthy development and use of AI.[58] In 2017, China announced the AI Development Plan and has several national-level policy documents for AI regulation and governance.[59] The EY 2024 Geostrategic Outlook Report mentions the dual race of developing AI and regulating AI as one of the cornerstones of AI's geopolitics, which is expected to accelerate and harden geopolitical blocks. For manufacturing, differences in policies regarding the development and regulation of AI and new technologies can significantly impact competitive conditions and create favourable environments in some industries and nations compared to others.

Economic tipping points

The global manufacturing sector faces potential economic tipping points that could drive innovation and growth or lead to disruptions and decline. Understanding these tipping points is essential for policymakers, business leaders, and other stakeholders who must navigate this complex landscape to ensure the sector's long-term viability and competitiveness.

Obsolescence of manufacturing business and operating models

Due to rapid technological advancements, traditional manufacturing businesses and operating models must be updated, making innovation essential for maintaining competitiveness.

The obsolescence of traditional manufacturing businesses and operating models is the most significant economic tipping point facing the sector today. This phenomenon is closely linked to the broader shift towards Industry 4.0, which involves the integration of advanced technologies such as automation, digitisation, and interconnected systems. These technologies are transforming the foundation of manufacturing businesses, leading to a fundamental change in how value is created, delivered, and captured in the market.

Historically, manufacturing companies have focused on incremental growth through product improvement and market expansion. This approach, however, is increasingly unsustainable in the face of stagnating economic development, global disruptions, and diminishing returns from traditional methods. Manufacturers who fail to innovate beyond product-centric strategies risk being outpaced by more agile competitors who are better equipped to navigate the complexities of the modern market.[60]

This potential for widespread industry disruption underscores why the obsolescence of traditional models is seen as a foundational economic tipping point. It affects every aspect of the manufacturing process, from supply chain management to production efficiency and market competitiveness.

Moreover, the need for business model innovation in manufacturing is becoming more urgent as environmental considerations, customer expectations, and regulatory pressures intensify. Manufacturing companies that successfully innovate their business models can achieve competitive advantages, cost efficiencies, and operational excellence. They can also respond more effectively to technological advancements, market changes, and regulatory requirements, positioning themselves for long-term success. Conversely, those who cling to outdated models face the risk of economic decline, as they may struggle to attract talent, meet sustainability goals, or maintain market relevance.

Wage inflation in key manufacturing hubs

Rising labour costs in crucial manufacturing hubs like China drive increased automation and relocation, reshaping the global manufacturing landscape and challenging the balance between cost effectiveness and technological investment.

Wage inflation in crucial manufacturing hubs represents another critical tipping point with far-reaching implications for the global manufacturing sector. As labour costs rise in traditional manufacturing powerhouses like China, manufacturing companies are increasingly exploring automation, outsourcing, or relocating operations to maintain profitability. This trend is reshaping the global manufacturing landscape and altering the economic calculus of production.

China, once the go-to destination for low-cost manufacturing, has seen significant wage inflation over the past decade. This trend is reaching an economic tipping point where manufacturing in China is no longer as cost effective as it once was. In response, companies like Foxconn, a major supplier for Apple, have started to automate production lines and shift some operations to lower-cost regions such as Vietnam and India.[61] This move highlights the growing importance of 'automation' in maintaining cost competitiveness and underscores the shifting dynamics of global manufacturing hubs.

The rise of automation is a tipping point that could reduce the reliance on human labour and shift the economic benefits of manufacturing from labour-intensive regions to those with advanced technological infrastructure. The widespread adoption of robotics in manufacturing, particularly in industries like automotive and electronics, is accelerating this shift. However, the balance between automation and cost effectiveness is complex. For instance, in 2018, Adidas announced the closure of its highly automated "Speedfactory" facilities in Germany and the US, citing inefficiencies and the high automation costs compared to traditional methods.[62] This case illustrates manufacturers' challenges as they navigate the tipping point between labour costs and automation.

The implications of wage inflation and automation extend beyond cost considerations. As companies increasingly rely on automation, there is a risk of significant job displacement, which could lead to social and economic challenges in regions heavily dependent on manufacturing jobs. Policymakers and business leaders must carefully manage this transition to ensure that the benefits of automation are broadly shared and that workers are equipped with the skills needed to thrive in an increasingly automated world.

Rise of raw material commodity prices

Fluctuating raw material costs and resource scarcity threaten manufacturing viability, prompting a shift to alternative materials and more resilient supply chains.

Raw material costs have always been a critical factor in manufacturing. Still, recent fluctuations have highlighted their potential to reach a tipping point where they jeopardise the economic viability of specific processes and products. The increasing scarcity of critical raw materials, driven by geopolitical tensions, environmental regulations, and supply chain disruptions, can lead to significant cost increases that could have far-reaching implications for the manufacturing sector.

The 2007-2008 global financial crisis saw a sharp increase in the prices of essential commodities like oil and metals, which strained manufacturing margins worldwide.[63] Manufacturing companies were forced to either absorb the costs, thereby reducing profitability, or pass them on to consumers, potentially reducing demand. The tipping point occurs when these costs reach a level where traditional manufacturing becomes economically unfeasible, prompting a shift towards alternative materials or localised sourcing strategies.

Resource depletion, particularly of rare-earth elements critical for electronics, presents another economic tipping point. The scarcity of these materials has spurred innovation in recycling and the development of synthetic alternatives. However, this also increases costs and potential disruptions in established manufacturing processes. For example, the push for electric vehicles (EVs) has driven up the demand for lithium and cobalt, leading to price surges and supply chain bottlenecks. These challenges underscore the importance of securing sustainable and resilient supply chains for critical raw materials.

The global semiconductor shortage in 2020-2021, exacerbated by geopolitical tensions and the COVID-19 pandemic, is a stark reminder of the vulnerability of global supply chains to raw material disruptions.[64] This shortage forced many manufacturers, particularly in the automotive industry, to halt production lines, highlighting the need for more resilient sourcing strategies. Manufacturing companies proactively managing their raw material supplies and investing in sustainable alternatives will be better positioned to navigate this economic tipping point.

Rise of energy prices

Volatile energy costs and the push towards renewable energy create challenges and opportunities, with green energy investments offering competitive advantages.

Energy costs represent another crucial economic tipping point for the manufacturing sector. Manufacturing processes are energy-intensive, and significant increases in energy prices can render traditional methods unsustainable. The global push towards green energy further complicates this landscape, as manufacturers are pressurised to transition to renewable sources, which often require substantial upfront investments.

Energy price volatility can severely impact the cost structure of manufacturing operations. For instance, during the 1970s oil crisis, many manufacturers faced existential threats due to skyrocketing fuel costs.[65] More recently, the shale gas revolution in the US provided a reprieve, lowering energy costs and boosting domestic manufacturing. However, reliance on fossil fuels poses long-term risks as regulatory changes and market dynamics shift towards renewable energy.

The transition to green energy presents challenges and opportunities for the manufacturing sector. Manufacturers that proactively invest in energy-efficient technologies and renewable energy sources can gain a competitive advantage. For example, Siemens has significantly reduced its carbon footprint by investing in renewable energy and energy-efficient production processes. Conversely, manufacturing companies that are slow to adapt may find themselves at a tipping point where rising carbon taxes or regulatory penalties erode profitability.

In addition to regulatory pressures, consumer demand for environmentally sustainable products drives the transition to green energy. Manufacturing companies that align their operations with these expectations can differentiate themselves in the market, while those that fail to do so risk losing market share. This dynamic creates a tipping point where the costs of inaction outweigh the investments required to transition to green energy.

Rise of logistics costs and supply chain risks

Rising transportation costs, regulatory changes, and supply chain disruptions force manufacturers to reconsider global supply chains and shift towards more localised production models.

Rising fuel prices, regulatory changes, and infrastructure challenges can lead to a tipping point where traditional global supply chains become economically unsustainable. This shift could force manufacturing companies to rethink their supply chain strategies and explore more localised production models.

Rising fuel costs directly impact transportation expenses, which in turn affect the overall cost structure of manufacturing. Changes in transportation regulations, such as stricter emissions standards, can further increase logistics costs. Implementing the International Maritime Organisation's (IMO) 2020 regulations, which required ships to use low-sulphur fuel, significantly increased shipping costs.[66] These regulatory changes are reaching a tipping point where traditional global supply chains may no longer be economically viable, leading to a reconfiguration of manufacturing networks.

The COVID-19 pandemic exposed the fragility of global supply chains, as lockdowns and transport restrictions led to significant disruptions. This situation highlighted the need for more resilient and flexible supply chains, with many manufacturing companies exploring near-shoring or reshoring strategies to reduce dependence on long-distance transportation. As manufacturers re-evaluate their supply chain strategies, the rising costs of transportation and logistics will play a crucial role in shaping the future of global manufacturing.

Shifts in global demand patterns

The growth of emerging markets and the expanding middle class are changing global demand, forcing manufacturers to adapt their strategies and production locations.

The global demand landscape is shifting, with emerging markets playing an increasingly significant role. As these markets grow, they are reaching tipping points that could fundamentally alter global manufacturing strategies. The rapid growth of emerging markets such as India, China, and Southeast Asia has shifted the focus of global manufacturing, with companies increasingly tailoring their strategies to serve these growing consumer bases.

The expansion of the global middle class, particularly in Asia, is creating new demand patterns that are reaching a tipping point. Most global demand may soon be driven by emerging markets rather than developed economies, forcing manufacturers to reconsider their product offerings, pricing strategies, and production locations. This shift has significant implications for the global distribution of manufacturing capacity and trade flows.

As labour costs rise in traditional manufacturing hubs like China, manufacturing companies are exploring lower-cost regions such as Vietnam, Bangladesh, and Africa. This shift could lead to a redistribution of global manufacturing capacity, fundamentally altering trade flows and supply chain dynamics. Nike's production shift from China to Vietnam is a prime example of how rising labour costs can trigger significant changes in manufacturing strategies.[67]

The growth of emerging markets also presents opportunities for manufacturers to tap into new consumer segments. Manufacturing companies that can successfully navigate the complexities of these markets, including regulatory challenges and local competition, will be well-positioned to capitalise on the expanding middle class. However, those who need to adapt to these shifting demand patterns risk being left behind in an increasingly competitive global market.

Global economic slowdown

Economic slowdowns trigger demand shocks, leading to overcapacity and industry contraction. This necessitates strategic fiscal and monetary responses to stabilise the sector.

A global recession or economic slowdown represents a significant tipping point that could lead to overcapacity in the manufacturing sector, forcing manufacturing companies to cut back production, close facilities, or even go bankrupt. The 2008 global financial crisis is a stark reminder of how a severe economic slowdown can lead to a tipping point in the manufacturing sector. The collapse in consumer demand during the 2008 crisis led to significant overcapacity, particularly in the automotive and electronics sectors, forcing many manufacturing companies to downsize or shut down operations. This experience underscores the manufacturing sector's vulnerability to demand shocks, which can have cascading effects on supply chains, employment, and overall economic stability. The COVID-19 pandemic similarly triggered a demand shock, leading to sudden and severe disruptions in manufacturing output. The pandemic led to a collapse in demand for non-essential goods, causing significant challenges for manufacturers worldwide. The tipping point occurred when supply chains collapsed, requiring substantial government intervention and restructuring of the sector.

John Maynard Keynes' theory of aggregate demand provides a valuable framework for understanding the impact of demand shocks on the manufacturing sector.[68] According to Keynes, a sudden drop in aggregate demand can lead to a vicious cycle of reduced production, job losses, and further declines in demand, creating a tipping point where the entire sector contracts. Policymakers must be prepared to respond to such tipping points with appropriate fiscal and monetary measures to prevent long-term damage to the manufacturing sector.

Social tipping points

Global social trends are reshaping societal structures and transforming jobs. The international manufacturing sector must understand these social shifts and prepare for a new generation of workers.

Workforce demographics

Significant social transformations in workforce demographics include declining fertility rates, which contribute to workforce shortages; increasing urbanisation, which alters the workforce profile; and the growing participation of women in the job market, which reshapes workforce composition.

World demographics rapidly shift, presenting significant social challenges directly affecting the manufacturing sector. Fundamental changes include an ageing workforce, generational differences, geographic redistribution, and increasing gender diversity.

According to the United Nations[69], the global population is expected to grow by 2 billion, from 7.7 billion to 9.7 billion by 2050, eventually peaking at nearly 11 billion by the end of the century as fertility rates continue to decline. Projections indicate that by 2050, 76% of countries worldwide will have fertility rates below the population replacement level.[70] Figure 7 illustrates current fertility rates, highlighting most countries' widening gap between younger and older generations.[71] As a result, the population and the labour force available for manufacturing are becoming increasingly older.

The labour-intensive competitive advantage some countries have historically enjoyed due to higher fertility rates is diminishing, as seen in China and India, producing workforce shortages. This change has raised the prospect of labour-intensive manufacturing relocating to Africa, the only continent where fertility rates remain high, potentially providing a young workforce for the future.[72] However, the widening generational gap in the manufacturing sector poses significant challenges. It represents a social tipping point for global manufacturing, creating critical workforce shortages that demand manufacturers to invest more in technologies to better cope with this new scenario.

At the same time, the global population is becoming increasingly urbanised, with over 50% of people now living in cities, a percentage projected to reach 70% by 2050.[73]

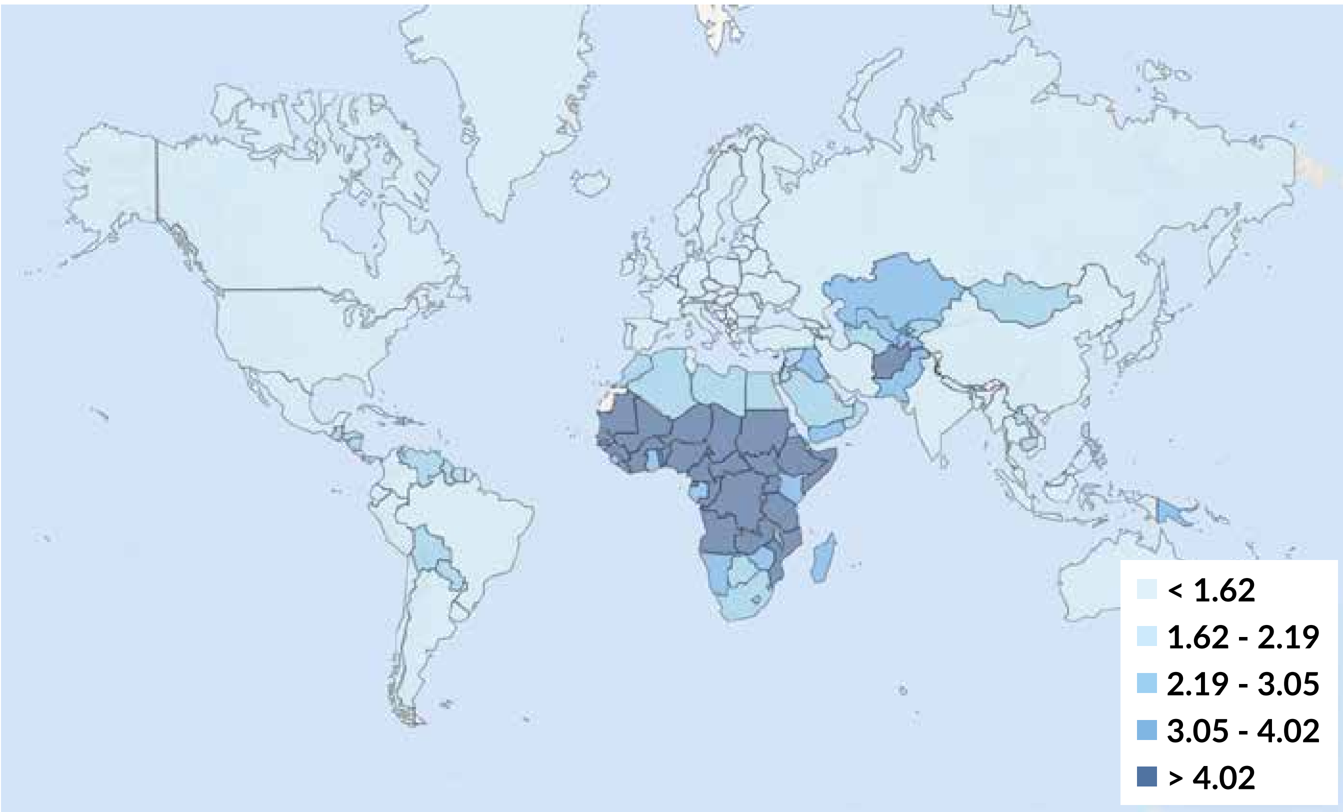


Figure 7

Fertility rates worldwide

(Source: World Bank, 2024)

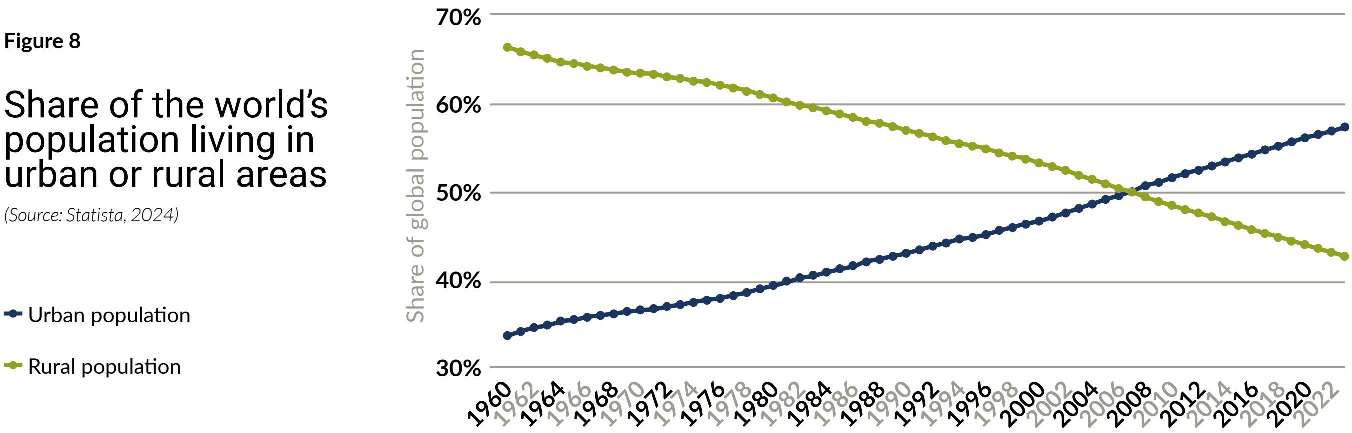
This significant shift towards urban living began less than 20 years ago, and urbanisation continues to accelerate, as illustrated in Figure 8. This trend presents another irreversible change that affects how manufacturing activity will be shaped. As workers become more urbanised, they encounter the complexities of urban life, which are often linked to increased anxiety, depression, and difficulties in achieving work-life balance. Consequently, manufacturing will need to address not only productivity concerns but also the emotional wellbeing of its workforce. Additionally, the proximity of urban workers to a diverse job market may lead to higher job mobility, potentially increasing turnover rates within the manufacturing sector.

As illustrated in Figure 9, female participation in labour markets has increased significantly over the last century in developed countries.[74] However, participation levels have stagnated worldwide, with less than 50% of working-age women in the labour market.[75] There are two distinct realities when considering women's labour market participation: developed countries have higher rates of women in the formal economy, while low-income countries see above-average rates of women in the informal sector. Emerging economies fall in between, with the lowest female labour participation rates.[76] In this context, gender diversity remains a challenge for the manufacturing sector, where women constitute only about 30% of the workforce in the US and Europe. This new reality creates a new workforce composition for the future of manufacturing.

Figure 8

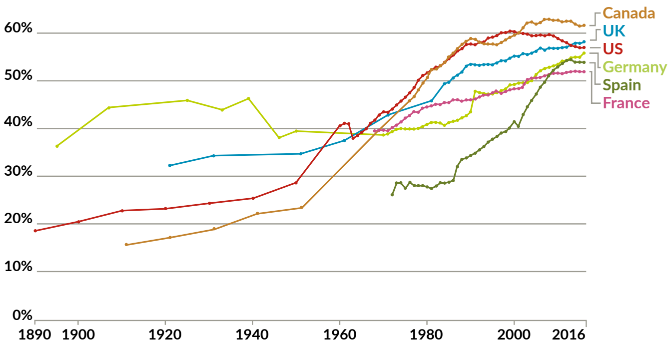
Share of the world's population living in urban or rural areas

(Source: Statista, 2024)



Share of women in the workforce

Proportion of the female population aged 15+ that is economically active.



Data source: Our World in Data Based on OECD (2017) and Long (1958)

Note: For some observations prior to 1960, the participation rate is calculated with respect to the female population aged 14+. OurWorldInData.org/female-Labor-supply | CC BY

Figure 9

Share of women in the workforce in developed countries

(Source: Our World in Data)

Skills gaps

More workers are needed with the in-demand skills necessary to transform the manufacturing sector sustainably. Due to society's changing needs, skills gaps have widened and could soon lead to significant shifts in industry.

Industrial transformations and technological advancements have significantly disrupted industries throughout history, altering the nature of work, the tasks performed, and the skills required. While these shifts have ultimately led to greater productivity, wealth, and wellbeing, such benefits are only realised when essential intangibles, like skills, are developed alongside new technologies. Introducing (new) technologies and setting new goals, particularly in manufacturing, can result in a productivity slowdown – also known as the productivity paradox.[77] This occurs when a mismatch between business needs and the workforce's skills creates skills gaps that hinder progress.[78] Moreover, demographic trends indicate a shrinking workforce, exacerbating challenges and leading to significant consequences.

Today, the manufacturing sector faces enormous challenges, ranging from the aftereffects of the pandemic to technological disruption and the green transition. A workforce that meets the demands of a competitive and sustainably growing industry is crucial for a functioning economy and society. The manufacturing sector needs a skilled workforce to maximise the benefits of technological advancements like artificial intelligence. However, the manufacturing sector today faces huge skills gaps and skills shortages, resulting in a slowdown or even stagnation in the transformation towards adopting new technologies needed to improve manufacturing systems' resilience, sustainability, and human-centricity.

Worldwide, 1.1 billion jobs are liable to be transformed by new technologies.[79] Within the advanced manufacturing sector alone, 29.9 million people are employed, and their jobs are impacted mainly by the implications of the green transition, the implementation of ESG factors, changing consumer behaviours, and the adoption of new technologies.[80] It is expected that around 44% of employees' skills will have to change, and the need for cognitive skills is growing the most.[81] However, only around 40% of adults upskill themselves yearly[82], even though many of their current tasks will disappear and new ones will be necessary. 74% of SMEs struggle to recruit the talents needed, mainly in construction, healthcare, and ICT jobs.[83] Since recruiting new talent will only become more arduous, manufacturing companies must balance this with internal training to equip their workforce.

Employees must have the right skills to remain competitive in the workplace and society. Studies show that up to 15% of tasks performed by US workers can be completed more efficiently – without compromising quality – by utilising Large Language Models (LLM)[84], potentially accelerating innovation.[85] Consequently, there is a substantial risk of falling behind in job performance and career advancement for those who need to adopt these technologies. However, in a rapidly evolving world, it is increasingly difficult for individuals to identify which skills are essential to acquire and develop.

With the current environmental crisis, the industry's priorities are shifting, and green innovation needs to be enabled. Hence, green skills have become increasingly important. Green skills are "skills required to adapt products, services or operations to meet adjustments, requirements or regulations designed to stem further climate change or adapt to the impact it already has".[86] While the commitment of individuals and industrial leaders is still too low to tackle the green skills gaps, the European Commission is pushing for a Green and Digital transformation (see Figure 10).

In the past, changing requirements have led to fear among workers of losing their jobs, realising that some of their tasks and skills are becoming obsolete. Looking at this from an evolutionary perspective, this fear stems from the survival instinct we humans have – we naturally want to stick to what is known, what we have experienced as functioning and safe.[87] This implies a particular difficulty in supporting employees through change management. A lack of inner motivation and transformational skills hinders people from adopting green practices. According to a study by the Inner Development Goals Foundation, these skills are "Being, Thinking, Relating, Collaborating, and Acting" (see Figure 11).

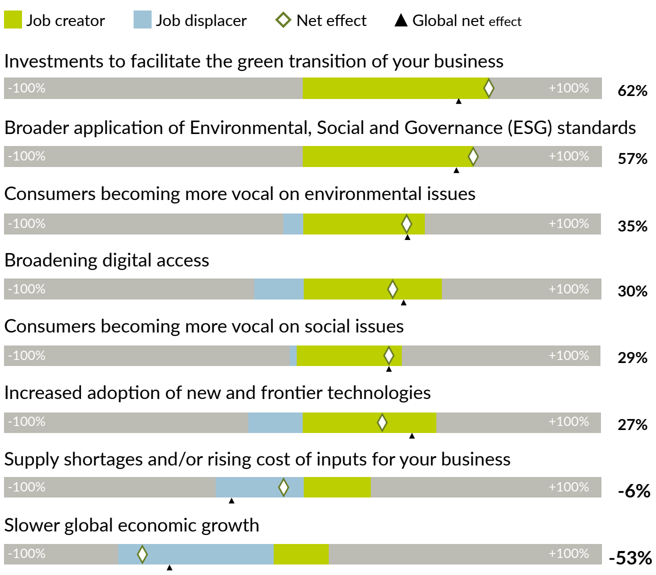


Figure 10

Global trends and their impact on job creation in the advanced manufacturing industries

(Source: WEF, 2023)

Figure 11

InnerDevelopmentGoals.org

Skills gaps significantly impact society, leading to threatened infrastructures, a slowdown in the green and digital transformation, and frustrated, polarised people.

The skills gaps in the manufacturing sector can lead to social inequalities, especially between those without access to education. Those with access to quality education can ensure they remain relevant in a changing environment with new requirements. However, people need access to educational resources to have the opportunity to follow the changes in the job market and eventually risk losing their jobs. This results in rising unemployment rates, more significant economic gaps between these two groups, and increased social inequalities. As an effect, this could increase the polarisation of society and put more fire into the arguments of radical groups. Society is close to a tipping point where it is about creating pathways accessible for everyone and leading to a workforce strong enough to work towards a sustainable industry or risk losing large numbers of people to unemployment and creating large societal instabilities.

The Sustainable Development Goals (SDGs) were set as directions to lead the world towards a sustainable future and prevent catastrophes. The SDGs "Decent Work and Economic Growth" and "Reduced Inequalities" highlight that employment and equal opportunities for all are needed to ensure a healthy and safe society. Unemployment leads to frustration and an increase in mental health disorders and suicide rates.

However, skills gaps in manufacturing can also lead to a tipping point for supply chains that rely on basic human needs. The lack of skilled workers who can produce the products society needs can lead to more supply chain disruptions, which can majorly affect society, mainly when critical goods, raw materials, or products are not delivered. From an economic perspective, skills gaps can lead to a decline in specific manufacturing sectors or even erase them. This would result from many reasons, all stemming from a loss of productivity and growth. Manufacturing companies need talented people to develop creative ideas, create innovative technologies, build sustainable solutions, and have a resilient and human-centric organisation. To do that, those people need to have the right skills.

Work-Life balance

The long working hours in manufacturing, one of the most demanding sectors, negatively impact work-life balance and can lead to irreversible health problems for workers and society.

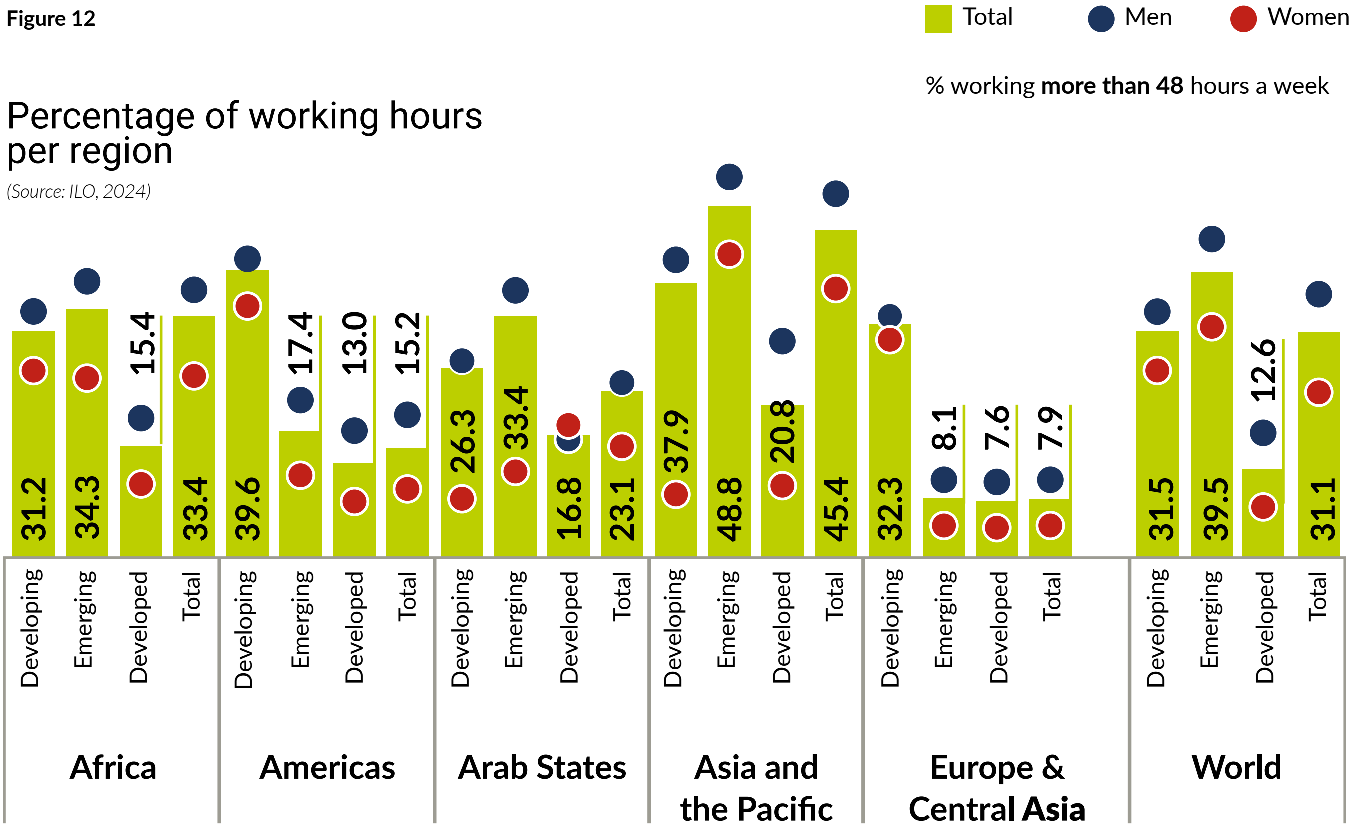
Work-life balance is critical for social sustainability, impacting workers' health and happiness. A healthy balance between work and personal life fosters a more engaged and committed workforce, contributing to a better society. One key metric for assessing this balance is the average working hours globally. The International Labour Organization monitors this trend, and Figure 12 compares average annual working hours across regions. While working hours have decreased in many countries over recent decades, developing and emerging nations still report high weekly working hours. The strain on workers' health from excessive working hours represents a tipping point for the future, especially as mental health becomes an increasingly urgent global concern.[88]

The manufacturing sector faces a unique challenge regarding work-life balance. As shown in Figure 12, it is one of the industries with the highest average weekly working

Figure 12

Percentage of working hours per region

(Source: ILO, 2024)



hours, at 47.6 hours. As a result, manufacturing workers are more prone to health issues and dissatisfaction in their personal lives, with limited time to pursue individual goals.[89] Organisations focused on improving work quality argue that these long hours must be reduced to prevent irreversible social issues, as seen in recent years with the rise of anxiety and depression in several societies.

Achieving a work-life balance model for manufacturing is a positive social tipping point that would create new work models focused on reducing the collateral effects of the current reality of work in manufacturing. In this sense, new perspectives have been proposed, including topics like human-centric manufacturing, industrial smart-working environments, and Industry 5.0, as models that can better integrate workers with technology and the organisation and provide better work models to create a more balanced work-life approach.

Diversity, equity, and inclusion (DEI)

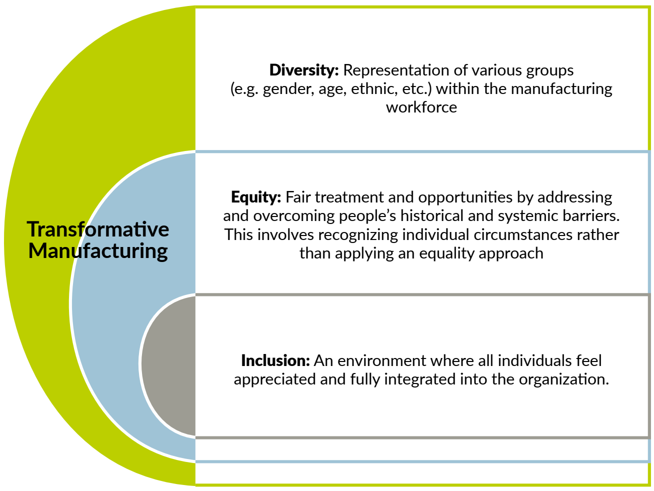
Increasing diversity, equity, and inclusion can help overcome workers' marginalisation and create a better environment. DEI can also foster creativity and innovation.

Focusing on diversity, equity, and inclusion (DEI) in the manufacturing sector has become increasingly crucial for future growth. In 2020, the global expenditure on DEI initiatives by companies (including those in the manufacturing sector) totalled US$7.5 billion, and there are projections that these investments will rise significantly, reaching US$15.4 billion by 2026.[90] Despite the previous efforts to include DEI as a critical business driver, the current rate of progress is still slow.[91,92] DEI-related advances vary among companies, industries, and countries. However, one inconvenient truth is that the manufacturing sector still lags in DEI, positing it as a tipping point. Figure 13 provides the DEI concepts.

Figure 13

DEI transformative manufacturing

(Source: 2021 Deloitte and The Manufacturing Institute DEI Study)

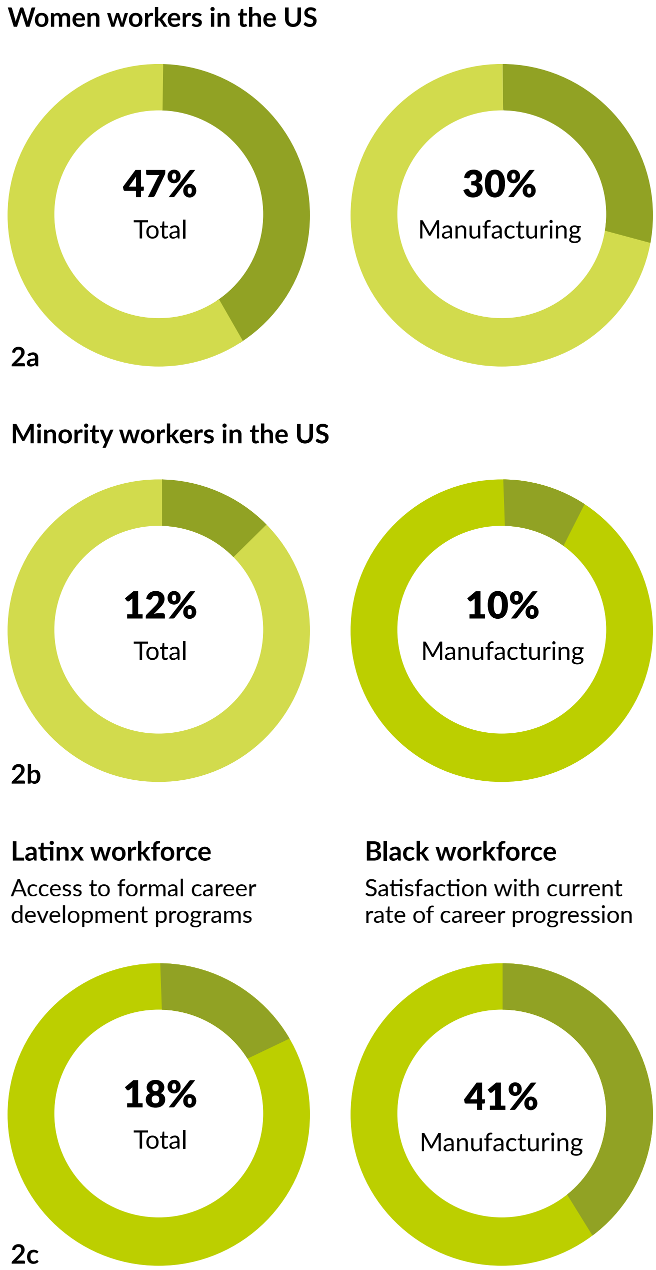


Some data highlight this inconvenient reality. As shown in Figure 14, only one-third of workers in the US manufacturing sector are women, while other minorities (for example, Asian and Latinx employees) have better representation.[93] Another study confirms the gender gap, with women comprising just 26% of all workers in the UK manufacturing sector. Additionally, only 5% of jobs are held by ethnic groups, and only 2% of manufacturers have an average workforce under 30.[94] In developing countries, generational, gender, and racial disparities also persist as well, where the representation of these groups remains significantly lower than that of their male counterparts.[95]
Moreover, Figure 14 shows that women and ethnic minorities frequently encounter disparities in wages, career progression, and promotions. Women generally earn about 20% less than their male counterparts, and promotion rates are also lower, as they are 20% less likely to advance.[96] Ethnic minorities face even more significant obstacles. Only 18% of the Latinx workforce has access to formal career development programmes, and just 41% of the Black workforce is satisfied with their career progression rates in the US industry sector. Unfortunately, similar situations concerning DEI are also evident for other minority groups.[97]

Figure 14

Diversity in the US manufacturing sector

(Source: Deloitte and The Manufacturing Institute DEI Study, 2021)



Considering current progress and ongoing efforts, achieving parity and diversity will take many years.[98] A clear negative impact is that these disparities and inequalities have led many individuals from these groups to leave or avoid the sector.[99] On the other hand, a positive effect is increased diversity, which is associated with more innovative environments.
Increased attention to DEI is necessary because it is the right thing to do and because imperatives are pushing the manufacturing sector. Some of them are related to demographic changes (ageing, racial justice, gender equality activism), consumer change behaviour (concerns about ethical practices), regulatory pressures (related to workplace diversity), and economic reasons. In this case, a study conducted by the Boston Consulting Group highlights that companies with higher levels of diversity experience innovation revenue that is 19% greater compared to companies with less diverse leadership.[100] Moreover, manufacturers with proactive DEI strategies have experienced increased productivity, better workforce motivation, and enhanced competitive advantage, as shown in Figure 15.[101]

Business benefits associated in fostering a diverse, equitable and inclusive organization

Figure 15

DEI and performance

(Source: Deloitte and The Manufacturing Institute DEI Study, 2021)

Changes in consumer behaviour

Societal values are shifting, and there is a growing concern for sustainable behaviour. As a result, consumers increasingly demand greater social responsibility from manufacturers in the marketplace.

The relationship between consumer behaviour and sustainability will strengthen in the coming years. A joint study by McKinsey and Nielsen analysed the sales growth of products claiming environmental and social responsibility.[102] The findings reveal that consumer-packaged goods with ESG-related claims in the US market experienced an average increase of 28% over the past five years, compared to 20% for products without such claims. The results indicated a correlation between manufacturers' commitment to environmental and social responsibility and consumer behaviour. Additionally, a 2022 BCG survey of 19,000 consumers across eight countries (Japan, the US, Germany, France, Italy, China, India, and Brazil) confirms that consumers have already embraced it.[103] There are key findings from this study. First, approximately 80% of consumers are alert to environmental and social issues. Second, 70% express disappointment with companies that engage in corporate greenwashing. Lastly, there is confusion among consumers about how they, as individuals, can contribute to sustainability. It is possible to conclude that there is a manifest intention to consume sustainable products. However, the survey also evidenced the "say-do" gap, as fewer than 8% of consumers are willing to pay a premium price for sustainable products. Considering all the results, manufacturers should make green choices more accessible and appealing to customers (for example, making sustainable claims). In doing this, they can close the gap between consumer intentions and spending.

Furthermore, McKinsey reveals that over 70% of consumers expect personalised experiences with products, services, and brands, demonstrating frustration when companies fail. Moreover, personalisation is particularly critical for younger generations, such as Millennials and Gen Z, who are already accustomed to individualised experiences.[104] However, although personalisation appears crucial, it does not ensure complete engagement, as brand exploration is another trend in consumer behaviour. Thus, Millennials and Gen Z are prone to exploring new brands and are five times more likely than older generations to believe that newer brands offer better or more innovative products than established ones.[105]

Technological tipping points

Is this the time to make or break? Evolution or revolution? Global manufacturing is under pressure amidst the grand manufacturing challenges and technological tipping points.

Enlarging industrial technological applications

Advances and adoption of new (deep) technologies are facilitating the achievement of new process efficiencies in the manufacturing sector.

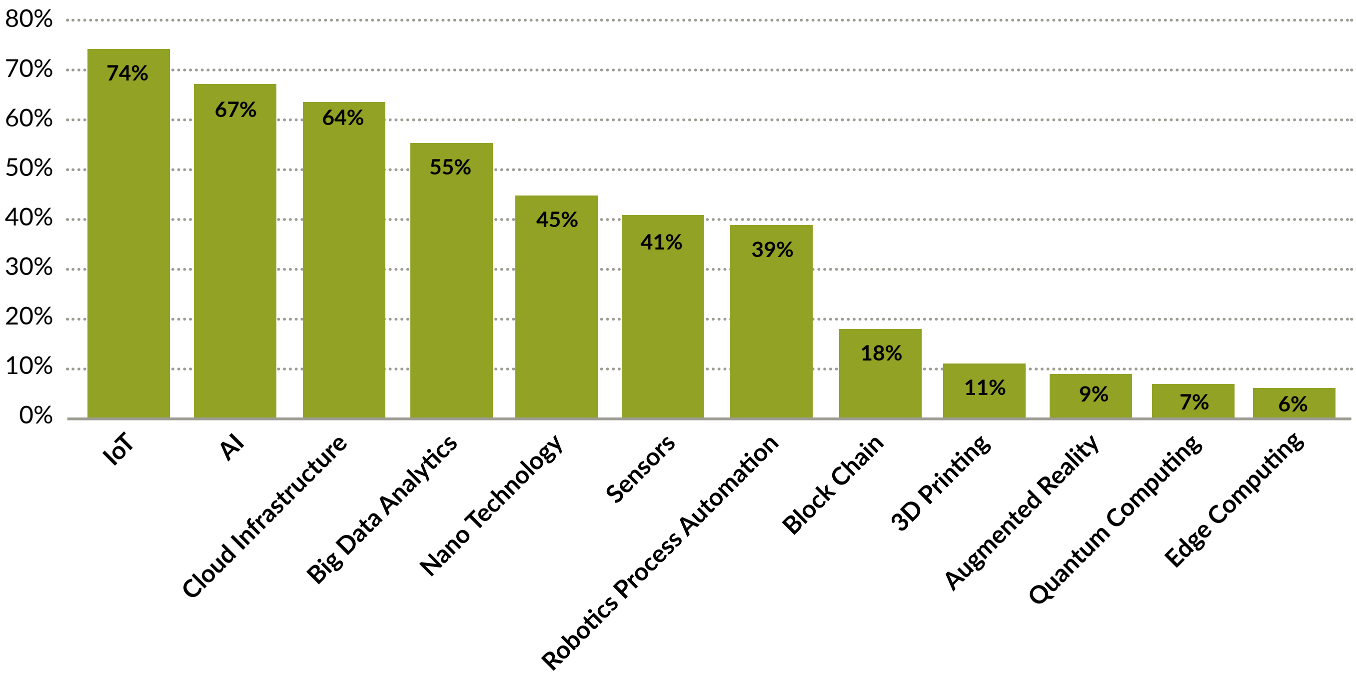
Digitalisation has led to the Fourth Industrial Revolution, and new (deep) technologies have changed the manufacturing landscape of possibilities. Manufacturers' resources are technologically optimised to create further avenues of opportunities. This has impacted previous design theories, existing designs, and how we perceive future designs to look, which have been revolutionised. Many studies have shown that smart systems have produced greater monetary benefits and provided a competitive advantage for manufacturing companies. However, if this fast-paced change is sustainable, reducing energy, resource intensity, emissions, and waste per production unit can be prioritised.[106] Scientists have agreed that 'sustainable innovations' create novelty regarding technology, processes, procedures, and practices involved in business models.[107]

Figure 16 shows the significant impact of IoT, AI, and cloud technologies on businesses.[108] The number of Internet of Things (IoT) devices in the world is forecast to almost double from 20.1 billion in 2025 to more than 39.6 billion IoT devices in 2033.[109] The widespread adoption of the Industrial Internet of Things (IIoT), where nearly every factory machine, sensor, and the process is connected and communicating in real time, is a game-changer. IIoT significantly enhances visibility and control over manufacturing processes, enabling real-time monitoring, predictive analytics, and more efficient resource management. This results in reduced downtime, increased efficiency, and more agile manufacturing systems that can quickly adapt to demand or supply chain disruptions.

Figure 16

Impact of digitalisation on businesses

(Source: Statista)



On November 30th, 2022, OpenAI introduced ChatGPT to the public, ushering in the debate on generative AI (GenAI) and its diverse applications. Industrial AI has been scrutinised for years but is increasingly considered and applied in practical production. AI-driven systems are increasingly involved in decision-making processes in manufacturing, from design and prototyping to production and quality control. AI can optimise production processes, predict maintenance needs (predictive maintenance), and improve supply chain management, leading to increased efficiency. It can also enable "smart factories," where AI continually optimises production systems. In literature, one of the primary reasons for implementing smart digitalisation through artificial intelligence (AI) in business models is to achieve mass customisation of products[110] and services; however, integrating technology innovation with smart business models is complex[111] and creates challenges for efficiency[112] and scalability. This leads to a "paradoxical" situation where the solution provider must effectively customise with AI and other smart technologies to satisfy customer needs while balancing cost efficiency (profitability) and sustainability without compromising efficiency and cost. It is estimated that the current market size (as of 2024) for digital transformation in global manufacturing stands at approximately US$1.38 trillion, with projections indicating a substantial increase to US$3.62 trillion over the next five years, as shown in Figure 17.[113]

Thanks to AI research and development advancements, intelligent and autonomous robots and automated systems have become available. They have greater flexibility and adaptability than conventional solutions, which enables them to perform more complex and precise tasks at scale.

Digital Transformation Market
Market Size in USD Trillion
CAGR 21.32%

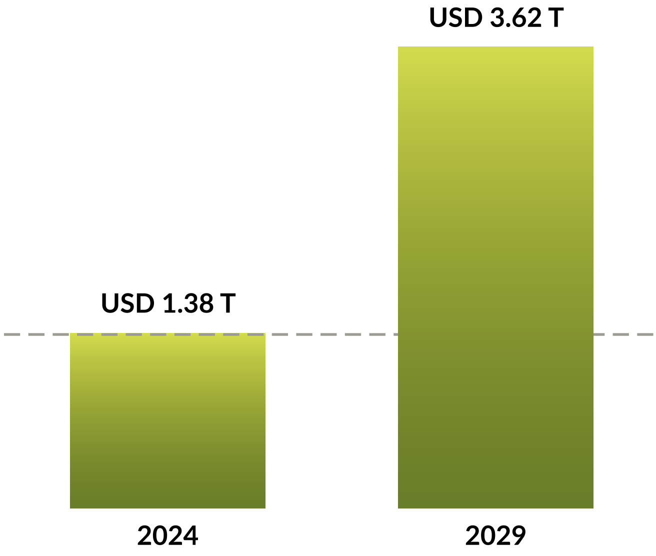


Figure 17

Projected digital transformation market sizes in 2024 and 2029

(Source: Mordor Intelligence)

Applying advanced robots and automated systems can result in increased productivity, higher consistency in quality, better ergonomics, and reduced labour costs. The manufacturing sector increasingly employs collaborative robots (cobots) working alongside human employees on factory floors, particularly for robotic automation. Cobots can perform repetitive and physically demanding tasks, allowing human workers to concentrate on more complex, creative, or decision-making roles. Cobots could enhance productivity, reduce workplace injuries, and lead to a more integrated human-machine work environment. However, increasing usage of robots and other automated systems could also lead to significant workforce changes, requiring reskilling and rethinking human roles in manufacturing.

Factories with more autonomous systems are becoming more realistic possibilities with AI, intelligent robots, and IIoT systems integrated, and they can operate with minimal human oversight. These factories can maximise efficiency, reduce human error, and operate continuously without downtime. While this could lead to cost savings and increased production capacity, it may also lead to significant challenges related to workforce displacement and the need for highly specialised technical skills. The increasing automation in manufacturing will require an adaptable workforce equipped with the necessary technical skills to operate and maintain these advanced systems. Global competition in the manufacturing sector intensifies, compelling a departure from traditional systems to meet new sustainability demands. This necessitates adapting durable industrial products to the principles of a circular economy, presenting the industry with various challenges. A pivotal challenge lies in the necessity to develop new materials possessing enhanced mechanical and sustainable properties, thus propelling the industry towards advanced manufacturing processes underpinned by Industry 4.0 technologies. These technologies facilitate the production of high-tech and intricate products while concurrently mitigating environmental impact.

Additive manufacturing (3D printing), robotics, edge computing, and machine learning (ML) have substantially transformed the manufacturing landscape. These innovations redefine product conceptualisation, manufacturing, and delivery, offering heightened customisation, precision, and efficiency. As contemporary manufacturing objectives grow increasingly intricate, traditional approaches necessitate revision, prompting enterprises to adopt novel and innovative strategies.

Additive manufacturing bears the potential to revolutionise the large-scale production of end-use parts across diverse industries, heralding a wave of optimism. This shift can revolutionise supply chains through localised, on-demand manufacturing, waste reduction, and the facilitation of highly personalised products. Conventional manufacturing processes, such as injection moulding, may experience diminished demand, while industries like aerospace, automotive, and healthcare benefit from the ability to fabricate complex, lightweight components. Additive manufacturing also allows the creation of highly customised and intricate products with complex geometries, incorporating elements from varied materials and embedded electronics, optics, or photonics. Despite offering an extensive range of design potentials, these products introduce challenges in terms of circularity and sustainability. However, additive manufacturing addresses some of these challenges by curbing material waste, reducing energy consumption, and supporting on-demand production, thereby significantly diminishing the environmental footprint of manufacturing.

The proliferation of industrial-technological applications confers substantial benefits, infusing a sense of hope. Additive manufacturing curtails wastage and facilitates rapid prototyping and customised production, reducing lead times, heightened flexibility, and the potential for distributed manufacturing. Smart automation and collaborative robotics further augment production precision and speed, while big data analytics and machine learning furnish insights for performance optimisation and cost reduction. As advanced materials and technologies gain pervasive traction, there is a drive towards hybrid manufacturing systems amalgamating traditional processes with innovative tools. New workpiece holding and tooling approaches empower seamless transitions between CNC machining and additive manufacturing, enabling heightened production flexibility. However, drawbacks endure, encompassing potential workforce displacement from an overreliance on automation and the substantial costs of adopting advanced manufacturing technologies, which may prove prohibitive for SMEs. Furthermore, integrating multiple technologies, materials, and processes introduces potential vulnerabilities such as production delays, quality control issues, or failures in automation systems, all of which can detrimentally impact the comprehensive manufacturing process.

Rising digital and green economy

There is a need for more governance systems as part of the digital economy.

An irreversible decentralised open database is created by blockchains, a new technological innovation that utilises peer-to-peer computing plus cryptography. A blockchain is a cryptocurrency, like Bitcoin, where the ledger maintains cash, but its entries may contain any information structure, encompassing ownership rights, identification and accreditation, agreements, etc. It is believed that the financial implications of blockchains embrace an expanded perspective of blockchains as an organisational technological advance, extending beyond the examination of new general-purpose technology and its destructive Schumpeterian consequences. How we own the asset is the new economy. According to the research argument, blockchains are an example of institutional change.[114]
Five distinctive principles of blockchain are peer-to-peer transmission, immutability of record, computational logic, transparency with pseudonymity, and a distributed database. Decentralised Finance (DeFi), Cryptocurrencies, Non-Fungible Tokens (NFTs), Gaming and decentralised Finance (GameFi), and a blockchain-based metaverse are all applications of Blockchain.

Disintermediation is the crucial idea of decentralisation. No single party controls the entire network, thus enhancing the distribution of power and authority, autonomy, and resilience. Decentralisation eradicates 'middlemen' or components from a transactional or supply chain. It entails eliminating pointless middlemen to create a closer relationship between manufacturers and consumers.
The manufacturing sector widely adopts blockchain, AI-driven analytics, and real-time tracking in supply chain management. These technologies can enhance transparency, security, and efficiency in supply chains. Manufacturers could achieve better product traceability, reduce counterfeiting, and optimise logistics, leading to faster, more reliable delivery of goods.
The current literature has forecast the growth of blockchain technology in business, primarily in information systems and management. However, it has yet to identify efficient application instances that could capture the curiosity of a wider population. Most blockchain research alludes to the system's features that affect how trust emerges in commerce.

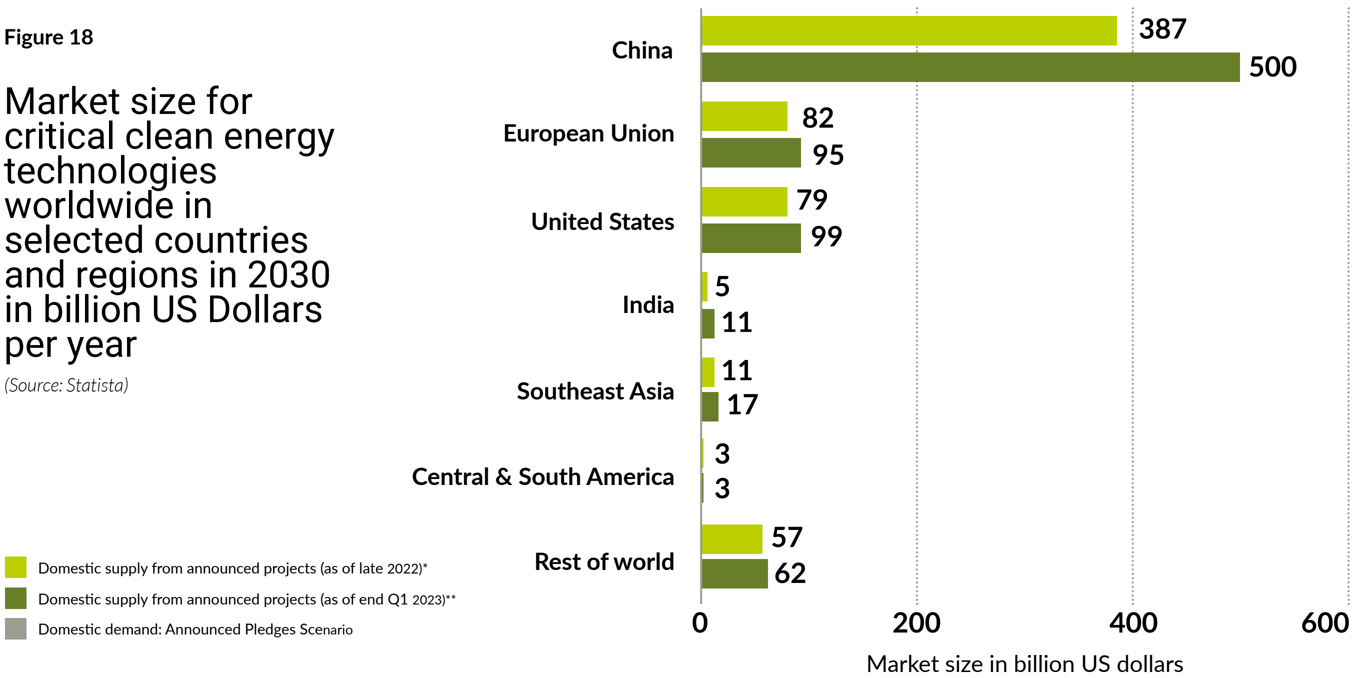
A Green Deal to become "clean" – the race for clean energy.

European industry accounts for about 20% of European greenhouse gas emissions. According to the EU Green Deal in 2019, it was decided that Europe will become carbon-neutral by 2050. The European Green Deal generates significant demand in the market for sustainable solutions. Technologies powered by artificial intelligence that enhance energy efficiency, minimise waste, and promote renewable energy sources are poised to find a receptive audience. Businesses could develop and invest in Clean Tech products and services that contribute to attaining sustainability objectives. As

Figure 18

Market size for critical clean energy technologies worldwide in selected countries and regions in 2030 in billion US Dollars per year

(Source: Statista)



shown in Figure 18, it is predicted that China will be the first in the race to keep the market share of clean energy technologies.[115]

Organisations that set the path towards technological investment and the European Green Deal could secure a significant advantage over their competitors. This is possible by embracing sustainable AI technological solutions ahead of others in the green technology sector. We can see that the Green Deal is now acting as a motivator/force for businesses to shift their business strategies and form new, reprocessed, renewal, and regenerative strategies that will follow the net-zero formula, optimise energy use, minimise waste, and reduce carbon footprints.

To aim beyond zero to become a net-zero sector.

On the industrial level, some tech companies' examples are Siemens and Capgemini, launching "Industry Net-Zero Accelerator" to get to net-zero operations by 2050. Given this, several manufacturers have signed up to support the cause and, in return, will be able to accelerate their emissions reduction plans. Another tech giant, Microsoft, has set a relatively short timeline and committed to being carbon-negative by 2030. They will be using 100% renewable energy by 2050. This sets the precedent for the tech market ecosystem and how decisions will be made to facilitate the reduction of customers' carbon footprint.
Some of the technologies with the highest potential to support cleantech include artificial intelligence, digital twins, virtual reality, augmented reality, big data analytics, blockchain, the Internet of Things, 3D printing, computer numerical control (CNC) machining, Industrial robotics, Cloud computing, and Digital modelling/prototype.

Circularity and sustainability by design as adoption drivers.

Manufacturers are forced to rethink their production methods with circular economy objectives to ensure the sustainability of durable industrial products. These new sustainability requirements demand that manufacturing systems be highly efficient and capable of extending product lifespan through better lifecycle management and monitoring while adhering to circular principles. As a result, international manufacturing must adopt flexible, transparent, trustworthy, efficient, and cybersecurity systems. Developing novel materials with enhanced mechanical properties and sustainability features pushes the industry to explore highly digitalised and circular processes covering the entire lifecycle. Enabling technologies like big data analytics, IIoT (Industrial Internet of Things), energy and resource management, AI optimisations, Digital twins and simulations allow manufacturers to achieve effective and efficient systems while reducing environmental impacts. Using simulations and the industrial metaverse can drastically cut down the resources needed to create working prototypes, helping to save both energy and materials long before production even starts. By generating synthetic data instead of running machines for extended periods, companies can quickly gather the data required for training, cutting energy and material usage while validating AI systems with 70% less computing power. According to Accenture[116], these advancements could save an impressive US$131 billion in raw material costs, reduce product development expenses by US$6 billion, and lower embedded product CO_2 footprints by 281 million metric tons, all thanks to better lifecycle assessment (LCA) visibility and smarter decision-making. The study also found that adopting digital twins across more industries could unlock up to US$1.3 trillion in economic value and reduce CO_2 emissions by 7.5 gigatons by 2030.
A vital aspect of the digital and green economy is the ability to integrate real-time monitoring and data-driven decision-making into manufacturing processes. Digital twin technologies provide virtual representations of physical systems, allowing manufacturers to monitor and optimise production processes in real time, leading to more significant sustainability gains. These gains come in the form of reduced waste, lower energy consumption, and the ability to extend the lifecycle of products through better maintenance, reuse, and recycling practices. In addition, adopting Sustainability by Design (SbD) practices by collecting data from the entire product lifecycle will boost production sustainability and circularity. In Europe, initiatives such as Digital Product Passport (DPP) will become a game-changer as it will be mandatory for the Batteries and Textiles industries, with more industries to follow. DPP is a tool for collecting and sharing data on products' value chain aiming to enhance sustainable production, fuel value-chain sustainability, advance to a circular economy, illustrate environmental and recyclability attributes, generate new economic prospects, aid consumers in opting sustainably, enable authorities to ensure legal conformity, etc. Furthermore, big data analytics offers valuable insights into reducing carbon emissions and cost-saving measures. Manufacturers can optimise resource usage and improve production efficiency by analysing machine data and identifying inefficiencies. These advancements contribute to cost reduction and a smaller environmental footprint, which is essential for aligning with global sustainability targets. Besides, the production and usage data analysis supports the circular economy by promoting product reuse, remanufacturing, and recycling, reducing environmental impact. However, the transition to a digital and green economy has challenges. Cybersecurity risks are a significant concern as more devices and systems become interconnected through the IIoT. If proper cybersecurity frameworks are not in place, the increased connectivity

can leave manufacturers vulnerable to cyberattacks, which could disrupt production and compromise sensitive data. Finally, the high cost of implementing and maintaining such infrastructure for the entire products' lifecycle may be prohibitive for smaller manufacturers, limiting their ability to participate fully in the green economy.

Confrontation of humans vs. machines

The increasing implementation of technologies in business will eventually change the current workforce allocation. This change necessitates considering the confrontation of humans and machines.

According to the Human-AI technology report, AI is a form of extremely capable automation directed at highly perceptual and cognitive tasks.[117] The team performance in human-AI interaction depends on automation levels, autonomy, and the stage of knowledge-worker interaction. We must better understand political economy, cultural production, and AI's role in cultural democracy and relativism. Innovation managers use tools like ChatGPT to navigate these complexities, balancing task automation while enhancing human creativity.

They must ensure AI integration supports business goals while fostering creative growth and respecting cultural dynamics.

According to Fusion Skills, hybrid activities are performed by both humans and machines. Figure 19 compares human and machine hybrid activities proposed by Daugherty and Wilson.[118] On the one hand, we see the benefits of humans complementing machines by rehumanising time (reuse time saved by machines), responsible normalising (sustaining process/activities) and judgement integration (decision-making). Whereas, when AI gives human superpowers, it is done by extracting insights through AI by intelligent interrogation, extending the capabilities of AI systems through bots. For instance, it could be an automated scheduling agent by Clara Labs and holistic melding, where models are made to reimagine a company's business. The development of new skills continues with reciprocal apprenticing in humans and machines. This is an iterative and cyclical process. Both learn from each other. This process continues again by reimagining new models from scratch and so the process is repeated.

The degree of automation implemented in various functional task stages can significantly affect human workers' performance, with potential beneficial and detrimental outcomes. For instance, increased automation may alleviate operators' workload and enhance performance outcomes. Conversely, it may diminish the worker's situational awareness and foster an excessive dependence on automated systems. Therefore, organisational 3D collaboration and simulation platforms impact human worker performance in conjunction with AI-driven automation.

"Fusion Skills" reflect human and machine hybrid activities

Human and machine hybrid activities					
Humans complement machines			AI gives humans superpowers		
TRAIN	EXPLAIN	SUSTAIN	AMPLIFY	INTERACT	EMBODY
Rehumanizing time			Intelligent interrogation		
Responsible normalizing			Bot-based empowerment		
Judgement integration			Holistic melding		
Reciprocal apprenticing					
Relentless reimagining					

Graphic based on diagram from Daugherty and Wilson, Human + Machine: Reimagining Work in the Age of AI

Figure 19

Human and machine hybrid activities

(Source: Daugherty & Wilson)

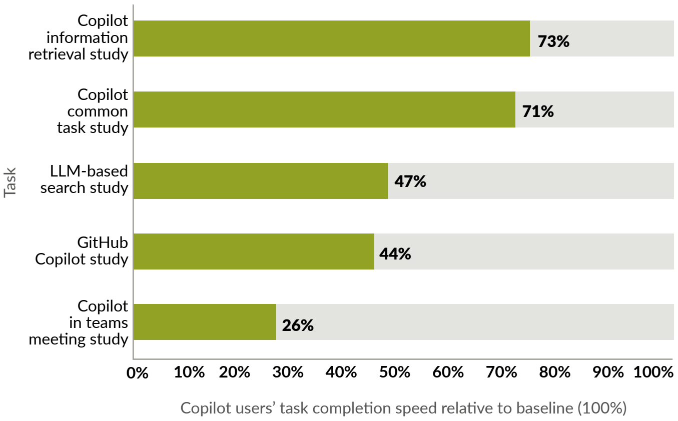


Figure 20

Cross-study comparison of task completion speed of Copilot users

(Source: HCAI)

As shown in Figure 20, the cross-study comparison shows the impact of AI on labour. The AI-enabled workers could perform their tasks better and more efficiently using Copilot. The study also showed that AI bridged the skills gap between low- and high-skilled workers. However, other studies show that using AI without proper oversight can cause performance to diminish over time.

Enlarging threats to digital privacy

The ever-connected industry makes sharing information and knowledge and accessing resources more convenient. Due to this accessibility, digital privacy issues are rising.

Integrating artificial intelligence (AI), the Industrial Internet of Things (IIoT), cyber-physical systems (CPSs), and virtual technologies holds significant potential for advancing the manufacturing sector's efficiency, sustainability, and innovation. However, these advancements are accompanied by the complexities of addressing potential workforce displacement, cybersecurity vulnerabilities, and the imperative of establishing new regulatory frameworks.

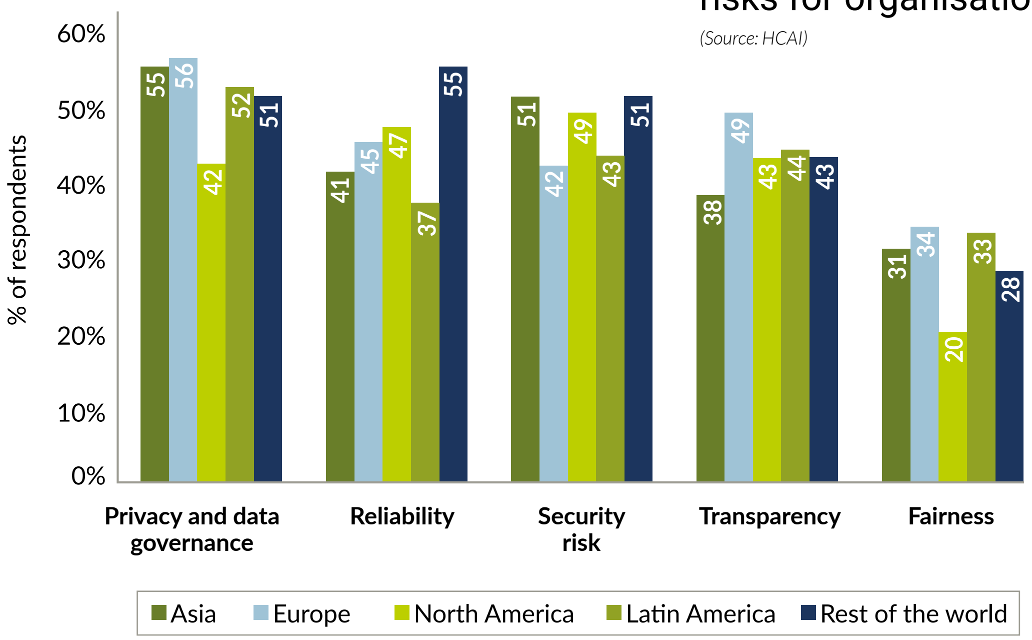
The susceptibility to cyberattacks escalates as the proliferation of the Industrial Internet of Things (IIoT) fosters ubiquitous data sharing and transfer among interconnected devices. Therefore, implementing robust cybersecurity measures and regulatory frameworks becomes paramount to fortifying the security of digitised systems and ensuring their resilience.

Moreover, utilising extensive datasets is crucial in training AI algorithms and large language models (LLMs) and developing data-driven solutions for industrial challenges. Despite prevailing regulations such as the General Data Protection Regulation (GDPR), the expanding scope of data acquisition presents persistent challenges to safeguarding digital privacy. Centralised and decentralised data storage strategies introduce distinct cybersecurity and privacy considerations. Figure 21 shows that privacy, security, and reliability are among the top global concerns of companies regarding responsible AI.

Figure 21

Relevance of selected responsible AI risks for organisations by region

(Source: HCAI)



A global survey on responsible AI highlights that companies' top AI-related concerns include privacy, security and reliability. The survey shows that organizations are beginning to take steps to mitigate these risks. However, globally, most companies have so far only mitigated a portion of these risks.

As the level of digitisation in the manufacturing sector increases, more data will be produced, and the industry will become more reliant on data. The IIoT, CPSs, and sensors generate and handle data flows which can be sensitive to the company itself or its customers. The shift towards interconnected processes and interoperable and hyper-connectivity systems increases the risks of cyberattacks that target critical infrastructures. Ransomware and data breaches from the IT level can halt production lines and reach the OT and ET levels, exposing proprietary information and compromising individual and customer data while causing revenue losses and delays in production, often leading to reputational damage. According to IBM[119], the average data breach cost in 2024 is US$4.88m, with a 10% increase over last year and the highest total ever. The same study suggests that adopting AI for Cybersecurity can save US$2.8m. According to McKinsey, this will intensify as data leaders must adopt an "everything, everywhere, all at once" mindset to ensure that data across the enterprise can be appropriately shared and used. However, only 32% have robust measures to secure the data used. This gap leaves manufacturers vulnerable to cyberattacks and internal misuse or unintentional exposure of sensitive information.

Emergence of cyber-physical systems

The emergence of cyber-physical systems (CPS) signifies a tipping point in modern manufacturing, reshaping the industry by integrating the physical and digital worlds. CPSs combine real-time data exchange, advanced computing, and physical operations, enhancing decision-making and optimising production processes. Key technologies driving this transformation include digital twins and the industrial metaverse. These enable manufacturing companies to simulate, monitor, and optimise operations, dramatically reducing resource consumption and improving efficiency.

Digital-twin technology, which creates virtual models of physical assets, has become increasingly common in manufacturing. Digital twins allow manufacturers to simulate and optimise processes, monitor performance in real time, and predict potential failures before they occur. This can significantly reduce development times, improve product quality, and lower costs by minimising errors and inefficiencies. For instance, a digital twin of a factory can model production workflows, identify bottlenecks, and suggest improvements, resulting in more streamlined operations.

An elaborated and advanced example of the industrial metaverse in action is Nvidia's Omniverse, which provides a real-time 3D collaboration and simulation platform. By using Omniverse, industries can create highly detailed digital replicas of their production environments, enabling teams to collaborate virtually on product design, optimisation, and troubleshooting. The platform's ability to simulate entire factories and production lines helps companies accelerate time-to-market while reducing material and energy waste. Other companies, such as Siemens and Dassault Systèmes, offer similar platforms, providing integrated simulation, data analysis, and optimisation solutions across various sectors.

From real to synthetic data and back to affect reality.

Digital twins can support the generation of synthetic data, which can be used to train AI systems. Synthetic data replicates the conditions and variability of real-world environments, allowing manufacturers to model different scenarios without the need for physical testing. For example, a virtual production line can simulate thousands of operational scenarios, identifying potential points of failure and suggesting improvements to boost efficiency. This process reduces the need for real-world trial-and-error, cutting resource consumption and operating costs. It also speeds up new product development as more operational (OT) and engineering (ET) data become available for decision-making.

Moreover, AI-powered decision-making allows manufacturers to optimise processes in ways that were previously unattainable. By feeding digital-twin-generated synthetic data into AI models, companies can train systems to recognise patterns and adjust in real time, improving operational efficiency. A study by Gartner[120] suggests that by 2027, over 40% of large organisations worldwide will use a combination of Web3, spatial computing and digital twins in metaverse-based projects to increase revenue. The same study indicates that JPMorgan Chase, the US investment bank, is betting on the metaverse being a US$1 trillion per year opportunity as it becomes the first bank to open in Decentraland – one of the world's most popular metaverse platforms.

Augmented Reality (AR) and Virtual Reality (VR) tools have become essential for design, prototyping, and maintenance in manufacturing. AR/VR can enhance training, enable remote collaboration, and allow real-time visualisation of complex designs or production processes. People with different roles and work locations can use VR to attend a joint event virtually and locally. Maintenance workers can use AR to visualise repairs or upgrades, improving accuracy and reducing downtime. For example, it is possible to show digital equipment overlays, providing step-by-step guidance on complex repairs. At the same time, designers can collaborate across geographies using VR, enabling multiple teams to participate in virtual joint events and design reviews faster.

The dark side of the "thirsty" AI-based digital twins.

While the benefits of cyber-physical systems are significant, there are notable challenges. One of the primary downsides is the high computational power

required for digital twins and simulations. Running these virtual environments requires substantial energy resources, particularly in data centres that support these complex models. Morgan Stanley estimates global data centre power use will triple this year, from ~15 TWh in 2023 to ~46 TWh in 2024[121], while Wells Fargo projects a surge of 550% by 2026.[122] If not managed sustainably, the environmental impact of supporting digital twins and other CPS technologies could offset some of the gains made in resource efficiency. Forbes details that the data centre was expected to require 1.3 million gallons of water daily from the county's main water supply.[123]
Furthermore, there is a risk that overuse of the different digital tools will gradually limit human creativity and critical thinking in problem-solving. As systems become more automated and AI takes on more and more decision-making responsibilities, the role of designers, engineers, and operators could shift from active problem-solving to passive oversight, handing over the "humanising" factors. This could reduce opportunities for innovation, as human workers become less involved in creative and complex decision-making processes, or decision-makers will lose trust in the human designers unless there is AI-backed evidence of success for their suggestions.
Lastly, the cost of implementing these technologies remains high. While large enterprises can afford to invest in digital twins, AI systems, and advanced computing infrastructure, small and medium-sized enterprises (SMEs) may find it challenging to keep up with these technological advancements. This could lead to a widening digital divide, where only well-resourced companies benefit from CPS and digital twins. This could reduce competition and innovation within the industry, forming digital monopolies and virtual exclusion.

Legal tipping points

"Legislators and regulators need to embrace an agile governance model, just as the private sector has increasingly adopted agile responses to software development and business operations more generally. They must continuously adapt to a new, fast-changing environment, reinventing themselves to truly understand what they are regulating." — Schwab (2016).

As manufacturing companies continue to push the boundaries of innovation, they find themselves navigating a complex legal landscape. The manufacturing sector operates in a vigorous regulatory environment, with governments and organisations worldwide grappling to keep pace with technological advancements.
Advanced technologies like AI, robotics, and the IoT are becoming increasingly integrated into industrial processes, with existing legal structures that must evolve to address new challenges and opportunities. This includes ensuring the protection of workers' rights, fostering digital inclusion, promoting sustainable practices, and safeguarding ethical standards in human-machine collaboration. Without timely legal adaptations, there could be gaps in safety, privacy, and social equity that could hinder the broader societal progress envisioned for the future of manufacturing. In the following, we explore legal aspects that include the need to be more human-focused while prioritising environmental sustainability and elements of resilience to guide regulations, laws, and standards as they create critical tipping points, driving the future transformation of the manufacturing sector. Such a panorama accentuates the need for legal support, such as regulatory actions that support companies.

Ethical human-technology symbiosis

The increasing symbiosis between humans and technology has highlighted the need to partner up for problem-solving. Creative tasks and promoting equitable digital empowerment and social cohesion are also needed.
Rather than technology merely being a tool for efficiency, it becomes an integrated partner in the manufacturing process. Thanks to the groundbreaking impact of AI, technology will be able to handle not only repetitive or dangerous tasks. Still, it will support human workers with creative problem-solving, innovation, and oversight. Human-AI teaming will generate a shift in the roles of workers and technology, which must also be redefined in legal terms in light of the fast-changing AI environment.
The increasing partnership between humans and technology raises challenges, including data privacy, accessibility, usability, equality and universality.
Embedding human values into legal and regulatory structures can foster technological advancements that drive innovation, enhance human wellbeing, and promote a more equitable society. Human wellbeing is an essential economic measure to complement traditional measures of national output. Organisations are being judged not only on their return on their owners' investment but also on broader issues, such as how well they fulfil their responsibility to society. Inspired by Japan's Society 5.0, an increasingly human approach to manufacturing seeks to harmonise the strengths of humans and machines, aiming to enhance creativity, human wellbeing, problem-solving abilities, and overall factory productivity.[124]

The following overview focuses on critical global and regional regulatory frameworks that are likely to shape the future of manufacturing.

Global regulatory frameworks

The United Nations Sustainable Development Goals (such as SDG8) set ambitious goals related to the need to guarantee decent work conditions, reduce inequalities, ensure good health and wellbeing, and move towards responsible production and consumption. There is a concerted effort to develop global standards on the international stage.

At the organisational level, international standards like ISO 27500:2016 and ISO 26000:2010 represent a pivotal reference point for companies that wish to become more focused on human wellbeing by optimising performance, minimising risks, maximising wellbeing in their organisation, and enhancing their relationships with customers. In a factory environment, the ILO Convention 155 on Occupational Safety and Health and the ISO 45001 on Occupational Health and Safety provide guidance and recommended actions by governments and within enterprises to promote occupational safety and health to improve working conditions.

At a technological level, standards are under development in several human-related fields. OECD and UNIDO foster responsible innovation as a trustworthy technology development guided by democratic values, responsive to social needs and accountable to society. Human-centred design guidelines, like the ISO 9241 series, ISO 27500:2016, ISO 20282 and ISO/IEC 25010:2011, provide recommendations and principles, including accessibility, usability, or ergonomics, for designing human-centred computer-based interactive systems. By embracing the principles outlined in the ISO Norms, organisations can create products and services that meet users' needs and contribute to society's greater good. In doing so, they can foster innovation, promote wellbeing, and create a more inclusive and sustainable future for all.

Regional regulatory frameworks

The ERA Industrial Technology Roadmap on Human-Centric Research and Innovation is at the forefront of regional frameworks and implements the European Commission's Industry 5.0 vision. It identifies a 10-year plan (up to 2035) for implementing strategies towards a Human-Centred Enterprise. In the document, human-centricity is "a multidimensional framework that places human needs, characteristics, motivation and experiences at the centre of design, development, and implementation of technological solutions and organisational practices that not only meet functional requirements but also enhance human wellbeing, capabilities, skills, and working conditions."

Human-centric research and innovation also involves several laws and regulations, including data privacy regulations and health and safety regulations, among others, aiming to implement the concept of a novel industrial humanism through the 20 guiding principles of the European Pillar of Social Rights. For example, the General Data Protection Regulation (GDPR) mandates transparency in data collection, user consent, data security, and the right of individuals to access and control their personal data. This regulation is crucial for ensuring that data collected from technologies used in smart factories, such as AI systems, is handled responsibly and ethically.

The European Framework Directive on Safety and Health at Work (Directive 89/391 EEC), adopted in 1989, was a substantial milestone in improving workplace safety and health. In 2004 the European Commission issued a Communication (COM [2004] 62) on the practical implementation of the provisions of some of the directives, namely 89/391 EEC (framework directive), 89/654 EEC (workplaces), 89/655 EEC (work equipment), 89/656 EEC (personal protective equipment), 90/269 EEC (manual handling of loads) and 90/270 EEC (display screen equipment)]. More recently, the Corporate Sustainability Reporting Directive (CSRD) requires companies to disclose what they see as the risks and opportunities arising from social issues and the impact of their activities on people.

In particular, ethical considerations surrounding AI and algorithmic accountability are also gaining prominence. The EU has adopted a regulatory approach to ensure the responsible use of AI and to address the risks posed by AI to fundamental rights. In December 2023, the trialogue negotiations between the European Commission, the European Parliament and the Council of the EU led to an agreement on harmonised rules on AI in the form of the EU AI Act.[125] Some months later, the new AI Convention[126] was signed by EU members, the US and the UK. This convention will be the first legally binding international AI treaty, which promotes responsible innovation and mainly focuses on protecting the human rights of people affected by AI systems. It is separate from the EU AI Act.

Many countries are reluctant to adopt strict AI regulations like the EU due to concerns that such laws might impede innovation. However, the need to ensure responsible AI has increased through the rapid development of advanced AI systems, such as generative AI. In October 2023, the Group of Seven (G7) leaders, chaired by Japan, agreed on the Hiroshima AI Process Comprehensive Policy Framework. Due to the continuous rapid development of AI technologies, norms and regulatory environments on responsible AI are likely to continue evolving. These principles were developed by the OECD's AI Principles and Japan's Social Principles of Human-Centric AI, which were adopted in 2019. Businesses developing, providing and using AI systems must comply with the applicable norms while remaining attentive to upcoming regulatory developments.

This tipping point marks a decisive moment where the widespread availability and accessibility of human-centric digital technologies either bridge or deepen societal divides within and beyond the manufacturing sector. Norms and regulations should consider age-based society fragmentation, the digital divide between high-income and low-income geographical regions, and differences between large companies and SMEs (or even microenterprises).

This involves making technology affordable and accessible to everyone, regardless of socioeconomic status or education, and providing inclusive training and education to equip all individuals with the necessary skills to thrive in a digital and human-centric economy. Legislators are pushed to foster equitable digital empowerment that promotes job satisfaction, productivity, and social mobility by enabling diverse workers to participate in technological advancements to participate in technological advancements actively. However, if digital technologies are not democratised, there is a risk of creating a technological elite, deepening societal divides, and exacerbating income inequality.

Such a scenario could lead to job displacement for those unable to adapt and increased social fragmentation between those who benefit from digital progress and those who do not.

Enhanced regulations for carbon, biodiversity, ecosystem restoration, and pollution

As environmental sustainability becomes an increasingly critical concern, the legal frameworks governing manufacturing are undergoing significant transformation. In this sense, emission trade systems reduce national emission contingents, and border tariff systems force manufacturers to adopt cleaner technologies and more efficient production processes. Additionally, recent biodiversity regulation mandates stricter pollution control and waste management standards, pushing manufacturers, especially in the chemical and heavy industries, towards sustainable production, circular economy practices, and initiatives for ecosystem restoration, especially in the chemical and heavy industries. These changes are not merely incremental; they create tipping points that fundamentally reshape manufacturing companies' operations. The following overview focuses on critical global and regional regulatory frameworks that are likely to shape the future of manufacturing significantly.

Global agreements and frameworks

Global environmental agreements and frameworks are set to shape the future of manufacturing. These agreements establish broad, legally binding commitments that influence national policies and regulatory environments worldwide. The three critical global agreements likely to create major legal tipping points for the manufacturing sector in the coming decade are the Paris Agreement, the Post-2020 Global Biodiversity Framework, the UN Sustainable Development Goa, and its expected successor for 2030.

The Paris Agreement, adopted in 2015, remains the cornerstone of global climate policy. To achieve the target of limiting global warming to well below 2°C, the Paris Agreement requires signatory countries to submit Nationally Determined Contributions (NDCs), which outline their specific plans for reducing greenhouse gas emissions.[127] These NDCs are reviewed and updated every five years, with the following significant round of updates expected around 2025. Manufacturing companies worldwide must comply with increasingly rigorous emissions standards as nations work to meet their updated NDCs. This could involve tighter limits on allowable emissions, mandatory carbon compensation measures, or introducing enhanced carbon pricing mechanisms.[128] These NDCs are reviewed and updated every five years, with the following significant round of updates expected around 2025. Manufacturing companies worldwide must comply with increasingly rigorous emissions standards as nations work to meet their updated NDCs. This could involve tighter limits on allowable emissions, mandatory carbon offsetting measures, or introducing enhanced carbon pricing mechanisms. Adopting more aggressive carbon pricing strategies, such as expanded carbon taxes or emissions trading systems, will impose additional financial burdens on carbon-intensive manufacturing processes, pushing companies towards adopting low-carbon technologies.

The Post-2020 Global Biodiversity Framework, adopted under the Convention on Biological Diversity, is another critical international agreement impacting the manufacturing sector. This framework sets out targets to halt and reverse biodiversity loss by 2030, emphasising the need for sustainable production practices, pollution reduction, and the restoration of ecosystems.[129] The framework's emphasis on reducing the ecological impacts of industrial activities is particularly significant for the manufacturing sector. Industrial processes contribute to biodiversity loss through pollution, resource extraction, and habitat destruction. The Post-2020 Global Biodiversity Framework aims to address these issues by pushing for stricter regulations on pollution control and sustainable resource management, pushing the adoption of circular economy practices. It will be particularly relevant for sectors involved in producing and managing hazardous substances, such as chemicals and heavy industry.

The United Nations Sustainable Development Goals (SDGs), adopted in 2015 as part of the 2030 Agenda for Sustainable Development, have provided a comprehensive framework for global action on various issues, including environmental sustainability.

Of the 17 SDGs, several have direct implications for the manufacturing sector, particularly those focused on responsible consumption and production (SDG12), climate action (SDG13), clean water and sanitation (SDG6), and affordable and clean energy (SDG7). Since their adoption, the SDGs have influenced national policies, corporate strategies, and international regulations, encouraging manufacturing companies to adopt more sustainable practices. Discussions about what might follow are underway as the 2030 deadline for achieving the SDGs approaches. The United Nations and its member states are expected to develop a successor framework that builds on the progress made under the SDGs while addressing emerging global challenges. This new framework could include more specific targets and be updated to reflect technological advancements, changing economic conditions, and evolving environmental priorities.

Regional agreements and frameworks

Regional environmental regulations are set to significantly impact the manufacturing sector. These regulations will enforce tighter controls on emissions, resource use, and sustainability practices. This section highlights critical national and regional frameworks in the European Union (EU) and the United States (US), as well as China and Japan, which are expected to create major legal tipping points for manufacturing.

The EU is pushing environmental regulation, with its European Green Deal and the Fit for 55 package setting the stage for transformative changes across all sectors, including manufacturing. The Green Deal, aiming for climate neutrality by 2050, includes a set of policies designed to reduce greenhouse gas emissions and promote resource efficiency. Expanding and revising the EU Emissions Trading System (ETS), the world's largest carbon market, is central to the EU's strategy.[130] The ETS is being strengthened to cover more sectors, with tighter caps on allowable emissions and a progressive reduction of available carbon allowances. For the manufacturing sector, this means increased costs associated with carbon emissions, driving the need for cleaner technologies and more efficient production processes to stay within the regulatory limits. The Carbon Border Adjustment Mechanism (CBAM), slated for full implementation by 2026, represents another significant regulatory innovation.[131] The CBAM will impose a carbon price on imports of carbon-intensive goods, effectively levelling the playing field between EU producers and foreign manufacturers subject to stringent carbon regulations. This mechanism is expected to have wide-reaching implications for global supply chains, compelling manufacturers outside the EU to reduce their carbon footprints if they wish to maintain access to the European market. Additionally, the Corporate Sustainability Reporting Directive (CSRD), effective in 2024, will drastically expand the scope and depth of sustainability reporting for companies operating in the EU.[132] Under the CSRD, large companies must provide detailed disclosures on their environmental, social, and governance (ESG) performance, including specific metrics on emissions, resource use, and ecological impacts. For manufacturing companies, this means integrating sustainability more deeply into their corporate strategies and operations, as the directive emphasises transparency and accountability in environmental practices.

In the US, the Inflation Reduction Act (IRA) of 2022 represents a significant shift in federal climate policy aimed at catalysing the transition to a clean energy economy. The IRA introduces extensive tax credits and subsidies that incentivise adopting renewable energy technologies, energy efficiency measures, and sustainable industrial practices. This legislation translates into substantial financial incentives for the manufacturing sector to reduce carbon emissions and improve energy efficiency, particularly in energy-intensive industries. The IRA also encourages the development of new technologies, such as carbon capture and storage (CCS). As these initiatives gain momentum, manufacturers will face growing regulatory pressures to align with the national strategy for climate mitigation, which includes achieving a 50-52% reduction in greenhouse gas emissions by 2030 compared to 2005 levels.[133] These measures are expected to reshape the manufacturing landscape, driving innovation and requiring significant investment in sustainable technologies to remain competitive in the US market.

China's drive towards stringent environmental regulation is anchored in its 14th Five-Year Plan (2021-2025), which strongly emphasises reducing carbon emissions, increasing renewable energy sources, and enhancing industrial energy efficiency.[134] These include more aggressive targets for reducing coal use and expanding renewable energy capacity, necessitating technological upgrades and operational shifts within the manufacturing sector. Furthermore, China is expanding its regulatory framework to include stricter enforcement of existing environmental laws and introducing new regulations, such as the Solid Waste and Chemical Management Law, which places additional responsibilities on manufacturers regarding waste disposal and recycling. The 15th Five-Year Plan is likely to continue these trends, embedding environmental sustainability into the national industrial strategy. This evolving regulatory landscape requires manufacturers in China to invest significantly in clean technologies and adopt more sustainable manufacturing processes to meet the new standards and capitalise on government incentives for green development.

Japan's environmental strategy for manufacturing is structured around its Green Growth Strategy, which was

established as part of the broader framework to achieve carbon neutrality by 2050.[135] This strategy includes plans to foster innovation and investment in green technologies across various sectors. For manufacturing, the focus is on promoting energy efficiency, reducing emissions, and encouraging using renewable energy sources. Key initiatives such as subsidies for carbon reduction technologies and the promotion of next-generation vehicles play a crucial role in driving the sector towards more sustainable practices.
The government's active role in supporting research and development in green technologies presents opportunities for manufacturers to lead in low-carbon innovation and sustainable practices.[136] As Japan continues to enforce and expand its environmental regulations, manufacturers must adapt by integrating eco-friendly technologies and processes, enhancing their domestic and global competitive edge.

In general, compliance directives drive manufacturers to deeply integrate sustainability into their operations, requiring comprehensive ESG disclosures and adherence to evolving global sustainability standards.

Global value chain disruptions

The evolving landscape brought about by global manufacturing advances has illuminated the increasing need for legal frameworks that promote resilience within the manufacturing sector. Companies strive to strengthen their manufacturing capabilities to remain competitive, creating an urgency to encourage legal measures. Still, they are not limited to acts, regulatory actions, and standards that support these efforts.

Global agreements and frameworks

The pursuit of resilience within the global manufacturing sector has reached tipping points caused by several disruptions of supply chains, which often result in significant negative impacts on product lines.

In the last decade, the COVID-19 pandemic and the Suez Canal blockage served as regrettable wake-up calls and exposed the risks of overreliance on a single source or region for critical components. Among some consequences, factories in crucial manufacturing hubs like China shut down, and companies faced severe disruptions. This has led to a strategic shift towards diversifying supply chains to reduce dependency on any one location and brought to light trends such as reshoring, nearshoring and similar strategies. Digitalised manufacturing environments require alignment with some identified legal objectives, among which can be found:

- *Building trust in data sharing:* Legal frameworks must prioritise establishing trust among stakeholders involved in data exchange, ensuring secure and reliable data flows.
- *Enhancing data availability:* Making data more accessible is crucial for informed decision-making and operational efficiency.
- *Eliminating technical barriers to data reuse:* Interoperability must be legally enhanced to facilitate the seamless reuse and sharing of data across different systems and platforms.
- *Clarifying data rights:* Providing legal certainty regarding data ownership and rights to prevent disputes and foster a cooperative environment.

Overall, the legal landscape must address the pressing issues of trust and interoperability in data-sharing legislation. As data becomes a central element of legal regulation, alignment is needed over a shared top-level metadata framework encompassing both intellectual property rights (IPR) and data rights.

Regional agreements and frameworks

- *Legal concerns in digital manufacturing* – The global semiconductor crisis, which lasted for over three years and disrupted the automotive industry, highlighted the need for action. In response, the European Union enacted the European Chips Act to create a robust framework that ensures supply chain security and resilience and strengthens the semiconductor ecosystem in the EU.[137]
- *Legal frameworks for digital resilience* – Legal ontologies have emerged from a perspective of traceability and interoperability. For example, the EU's Digital Operational Resilience Act (DORA), effective from January 2023 to January 2025, exemplifies a legal response to enhance financial entities' IT security.[138] By ensuring that the financial sector can withstand severe operational disruptions, DORA highlights the broader implications of digital resilience for other industries and the economy.

In conclusion, the last few years have driven manufacturers to re-evaluate how global value chains must be restructured to be more resilient in the face of disruptions caused by external factors to companies. This has illuminated the many legal actions presented in this section to increase resilience.

Environmental tipping points

"Every corporation is under intense pressure to create ever-increasing shareholder value. Enhancing environmental and social performance are enormous business opportunities to do just that." — Pfeiffer (2004)

Greenhouse gas emissions and climate change

Greenhouse Gas (GHG) emissions refer to the release of gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases into the Earth's atmosphere that trap heat, creating a 'greenhouse effect' that warms the planet. While this natural process is essential for life on Earth, as it keeps the planet's temperature at a level suitable for ecosystems to thrive, human activities since the Industrial Revolution have significantly increased the concentration of these gases in the atmosphere, leading to increased temperatures and a phenomenon commonly referred to as global warming. According to the last Intergovernmental Panel on Climate Change (IPCC) Assessment Report, human activities have unequivocally caused global warming (see Figure 22).[139] Global GHG emissions (measured in carbon dioxide equivalents CO_2e) set a new record of 57.4 $GtCO_2e$ in 2022, with an increase of 1.2% from the 2021 level.[140] Due to anthropogenic GHG emissions from fossil fuel combustion and industrial activities, land use and forestry changes, and fluorinated gases, in 2011-2020, the global surface temperature reached 1.1°C above the average temperature of the pre-industrial baseline of 1850-1900.

According to most recent data, the manufacturing sector is a significant contributor to GHG emissions since it is a major consumer of energy, much of which is derived from fossil fuels such as gas, oil, and coal (see Figure 23).[142] This reliance on non-renewable energy sources contributes significantly to the manufacturing sector's carbon footprint. In particular, the energy use in industry accounts for nearly 24% of total yearly GHG emissions due to the contribution of energy-intensive industries such as the manufacturing of iron and steel products (7%), which are hard to decarbonise; the production of chemical and petrochemical products such as fertilisers, pharmaceuticals, refrigerants, and oil and gas extraction (3%); the manufacturing of food and tobacco products (1%), which take into account the energy-related emission for converting raw agricultural materials into their final products; the production of non-ferrous metals (1%) such as aluminium, copper, lead, and zinc; and the energy-related emissions from manufacturing activities in other industries such mining and quarrying, construction, wood, textiles, and automotive. The manufacturing sector also contributes to direct industrial process emissions, which account for 5% of total GHG yearly emissions. GHG can be produced as a by-product of manufacturing and chemical processes. Production processes such as clinker production for the cement industry produce CO_2 as a by-product during the conversion of limestone to lime. CO_2 can also be emitted during the production of ammonia.

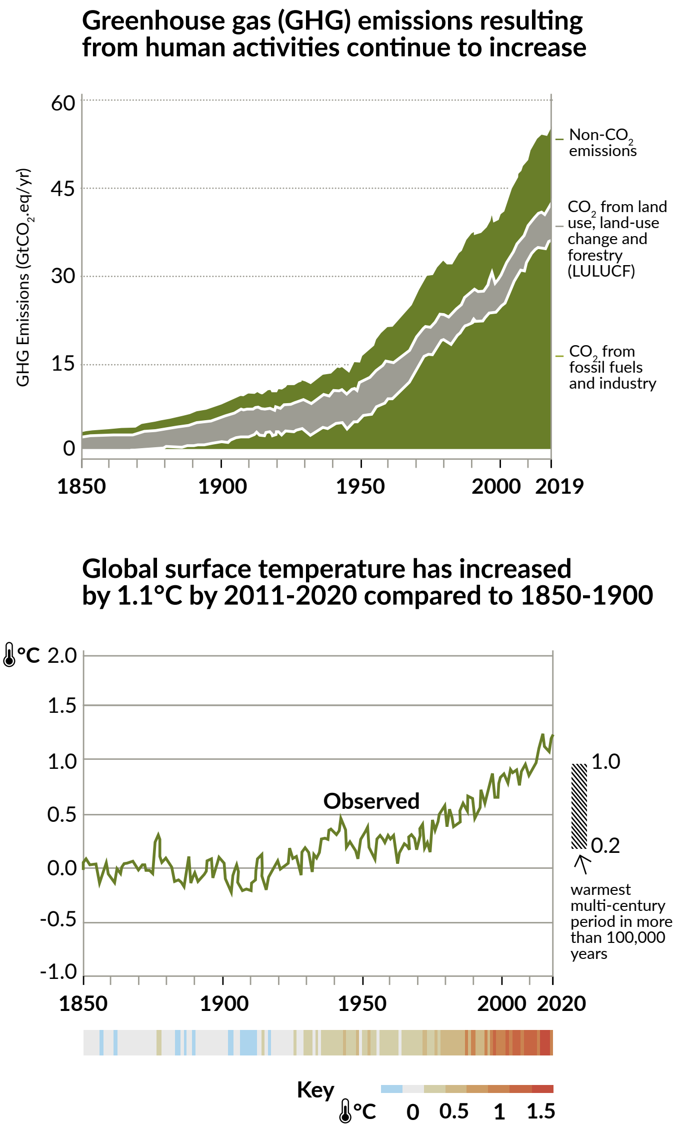


Figure 22

Global rise in GHG emissions and surface temperature from 1850 to 2020[141]

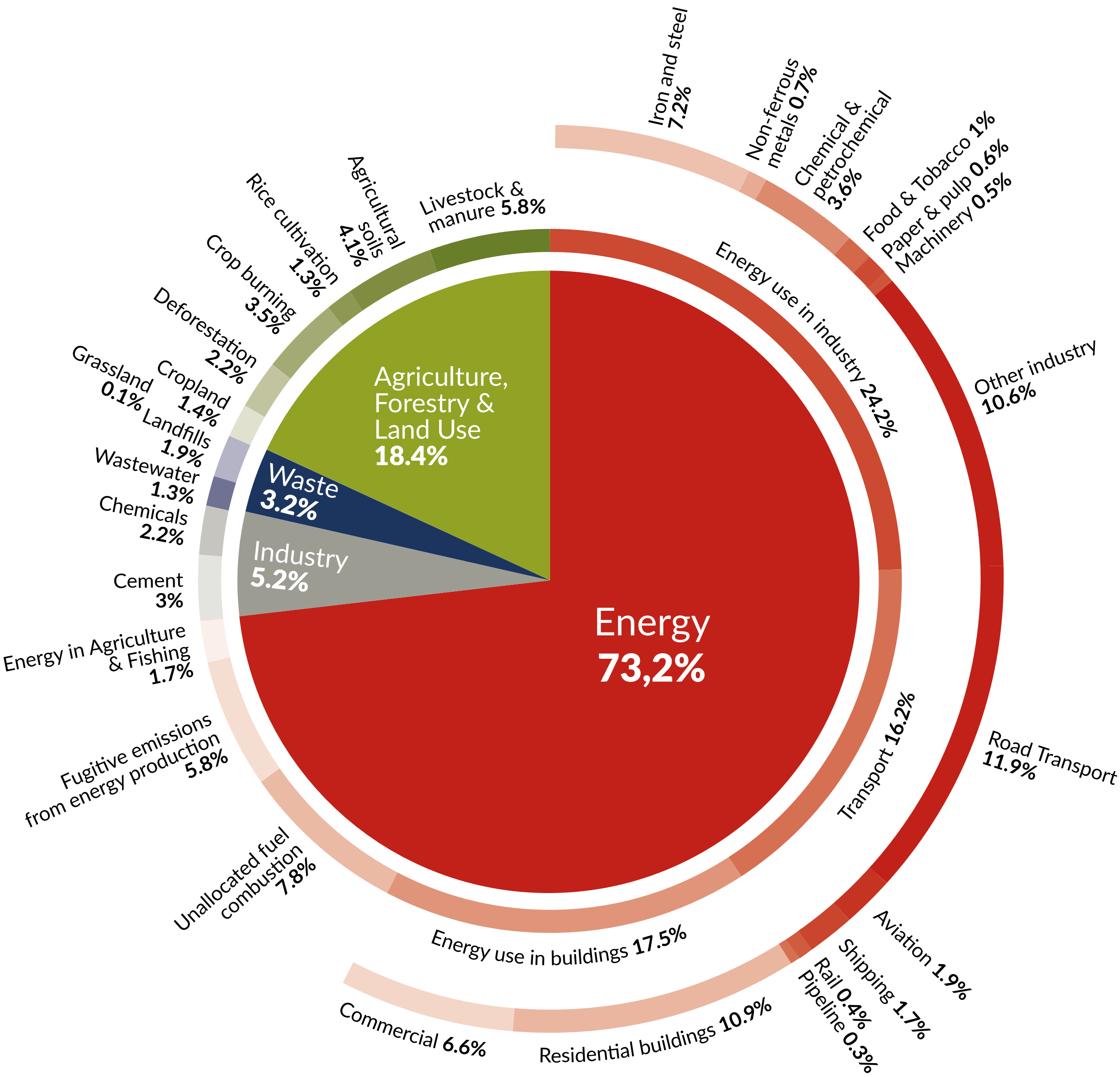


Figure 23

Breakdown of GHG emissions by sector[143]

Lastly, waste-related emissions can be generated from end-of-life products, especially if they are landfilled (2%). The manufacturing sector is directly and indirectly responsible for nearly one-third of global CO_2 emissions.

GHG emissions and global warming are significant drivers of climate change. Under the Paris Agreement[144] signed in 2015, countries agreed to reduce GHG emissions to keep the long-term global average surface temperature increase well below 2°C against pre-industrial levels and pursue efforts to limit it to 1.5°C. After almost ten years, however, research is warning that, under nearly all IPCC scenarios, the rise of temperature above 1.5°C against pre-industrial level and due to global warming will occur by the early 2030s.[145] This will cause long-term, potentially irreversible and self-perpetuating changes to planetary systems or human welfare, including hot temperature extremes, heavy precipitation, agricultural droughts, and ecosystem disruption. In particular, climate change is likely to lead to sea levels rising from collapsing ice sheets, carbon release from thawing permafrost, and disruption of ocean or atmospheric currents (see Figure 24). As a result, many economies will remain largely unprepared, threatening climate-vulnerable populations.

Biodiversity losses and damage to biosphere integrity

Biodiversity has a strong connection with climate change issues. Hence, global warming could affect its balance.

Figure 24

Negative expected consequences of crossing the climate tipping point by 2030[146]

If the temperature moves from 1.5 to 2°C, a reduction of the ranges of several species will be experienced: for vertebrates from 4% to 8%, for plants from 8% to 16%, and for insects from 6% to 18%. These percentages would be higher, reaching values equal to 26%, 44%, and 49%, if the temperature rose by 3.2°C.[147] Biodiversity is also highly linked to changes in forests (tropical, boreal and temperate forests). Together with global warming, deforestation may negatively affect forest resilience. To report some examples of tropical forests, as an indication, the Amazon rainforest has registered a loss of more than 75% in resilience towards temperature increase and rainfall reduction since the early 2000s. Moreover, the Amazon rainforest has always acted as a carbon sink due to CO_2 fertilisation. Still, based on simulated studies, a global warming increase of between 2°C and 6°C could provoke a nonlinear decrease in the properties of the Amazon rainforest. The temperature increase may cause water limitation, reducing plants' moisture transpiration on very short timescales (hours to days). Similar fast effects on rainfall can be registered due to deforestation, as the loss of trees can rapidly reduce evapotranspiration.[148] Another critical element regards the fire regimes, which are expected to increase next year if habits do not change. For example, in Canada and its boreal forests, the frequency of fires during the last century has increased, causing a decrease in coniferous forests. This phenomenon at large could cause a change in the forest microclimate; for instance, insects may expand into North American boreal forests, causing changes in ecosystem dynamics.[149]

Humans, with their habits, are substantially affecting the temperate forests. The dynamics of these types of forests are like those of tropical forests. Indeed, a reduction in forest coverage reduces atmospheric moisture supply, which provokes a decrease in the precipitation downwind and a parallel increase in heat, which may amplify drying and warming in the affected areas.[150] In parallel, Savannas that humans have used for centuries for agriculture are currently treated by forest invasion caused by the change in rainfall regime, fire diffusion, and increased CO_2 emissions.[151]

These tipping points show that systems are currently unstable, and their resilience is under attack due to external changes. Changing the forests and savannas would give out more CO_2 emissions, causing higher global warming.

Natural resources depletion

Looking at the country overshoot days, the resource usage pace is not under control (see Figure 25).[152]
This is even more crucial when we deal with critical raw materials that are impossible to substitute, have a complex supply, and are significantly economically important for key European sectors.

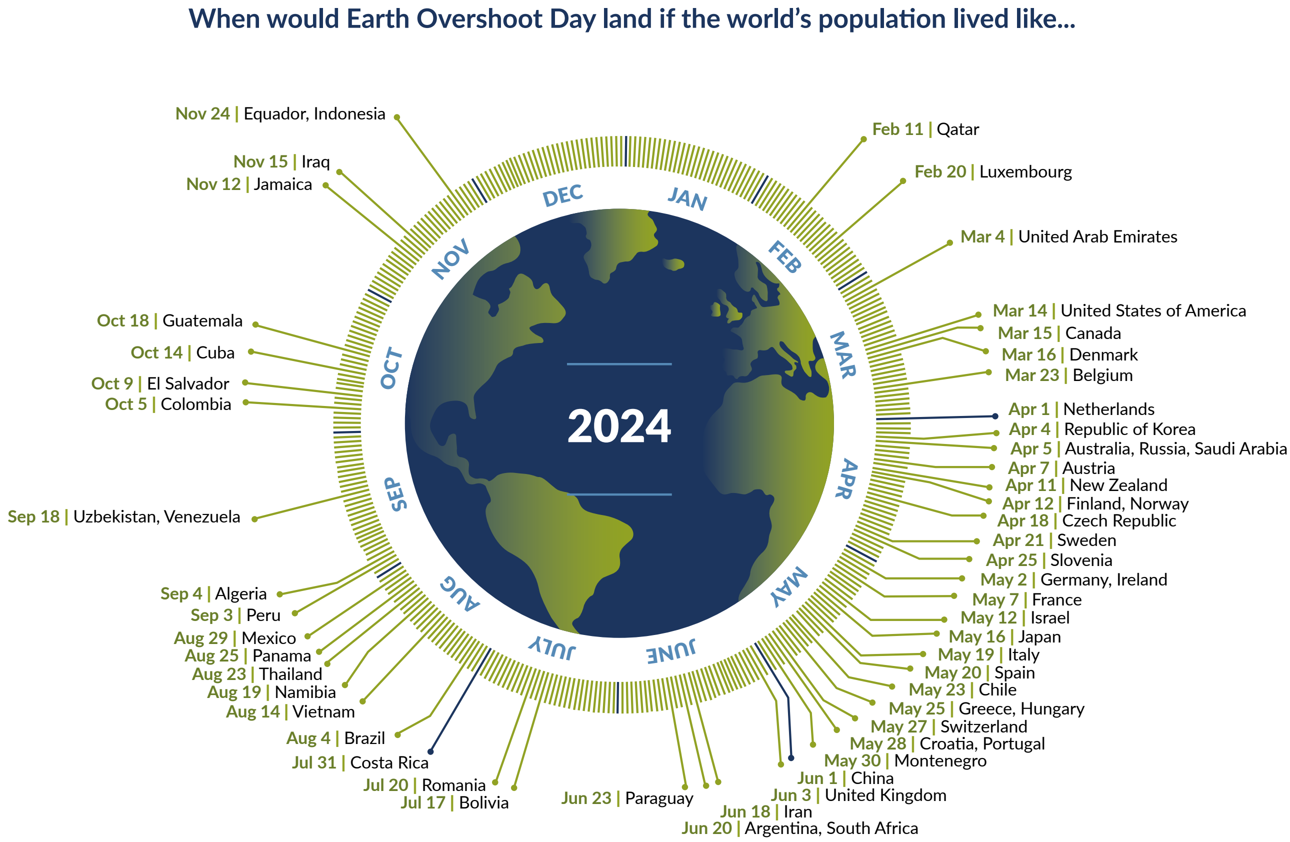


Figure 25

Country overshoot days 2024[153]

Considering their importance, the European Commission has set some targets for their extraction (10%), processing and refinement (40%), recycling (25%), and dependency on foreign countries (65%) by 2030.

One of the indicators that has been introduced to monitor resource efficiency (connected to the SDG8) is the material footprint. It is a demand-based indicator independent of where the materials come from, showing the requirements in terms of material. Figure 26 shows the data related to the material footprint registered in 2020 concerning regions and income groups.[154] According to the data collected, it is evident that waste management and resource recovery have a small footprint, while food, mobility and built environment are the most impactful, especially for high-income groups.

Waste generation

Lastly, the manufacturing sector generates vast quantities of waste, which is not biodegradable and can persist in the environment for decades. There exist different ways of

Shares of material footprint by five provision systems and regions and country income groups, 2020, percentage.

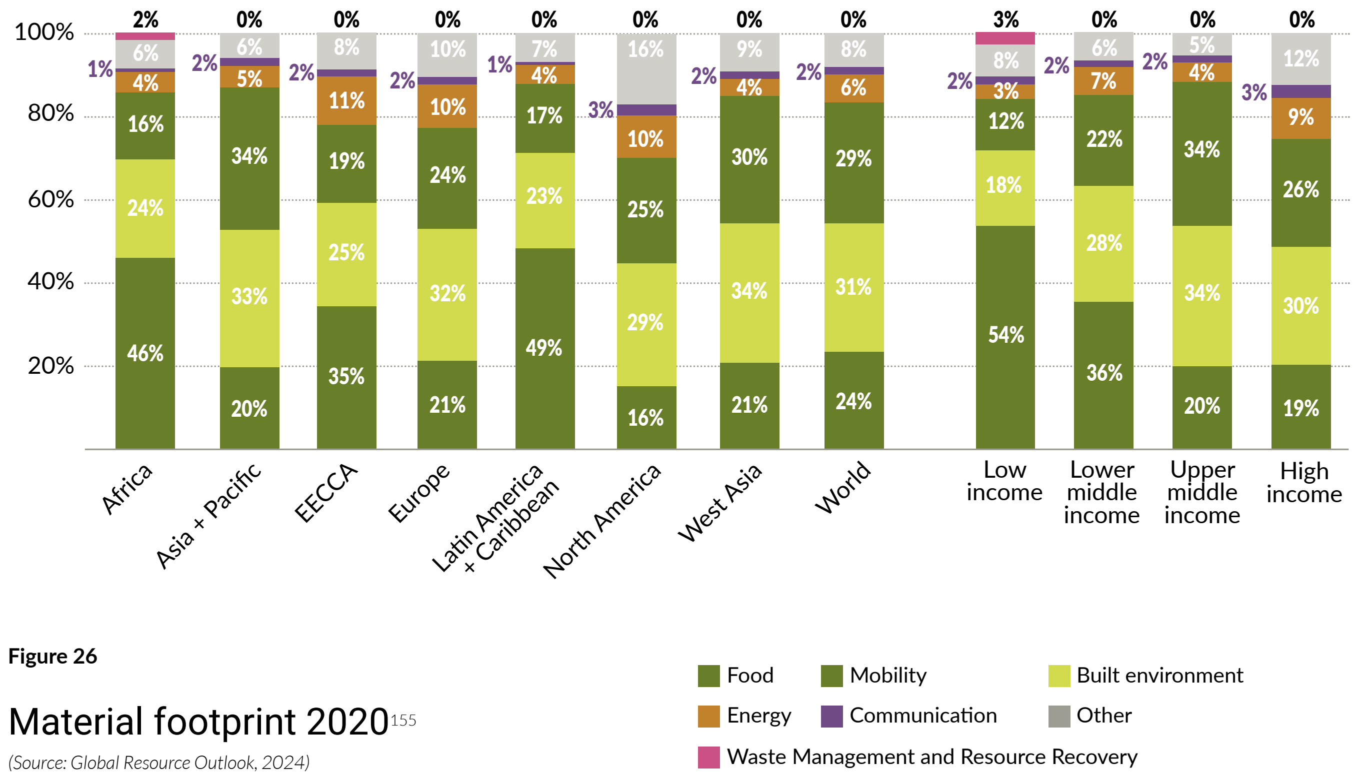


Figure 26

Material footprint 2020[155]

(Source: Global Resource Outlook, 2024)

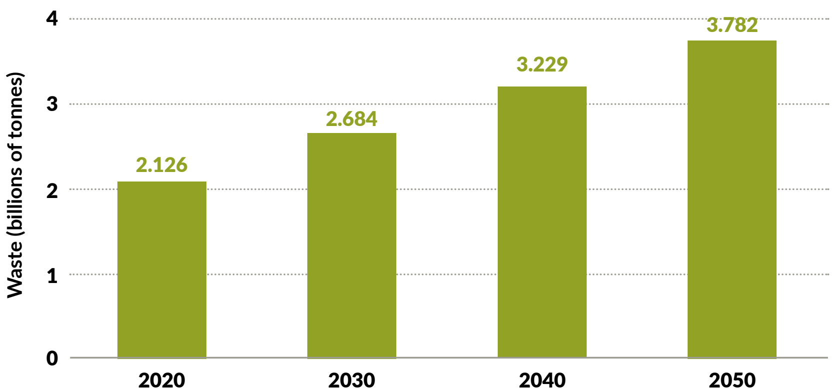
categorising waste. For instance, waste can be categorised by the type of material (plastic waste, food waste, etc.), by the source of waste origin (municipal solid waste, industrial waste, commercial waste, etc.), or by the product type (electrical and electronic waste, end-of-life vehicles, etc.).

The manufacturing sector is often entangled in generating industrial and product-related waste that arises when manufactured products arrive at their end-of-life). Industrial waste includes scrap materials, defective products, and packaging waste. This waste can be considered hazardous when it contains toxic chemicals that require careful handling and disposal. Improper industrial waste management practices can lead to soil and water contamination, posing significant risks to public health and the environment. Also, product-related waste

Figure 27

Projections of global municipal solid waste generation[157]

(Source: UNEP 2024 Global Waste Management Outlook)



has increased worldwide in recent years. A recent report from UNEP estimated that, in 2020, global municipal waste generation reached 2.1 billion tonnes per year worldwide (see Figure 27).[156] Owing to economic and population growth, this figure is projected to increase to 3.8 billion tonnes by 2050 (+56%) if no urgent actions are taken.

Delving deep into the electrical and electronics industry, the 2024 edition of the global e-waste monitor report showed that, in only 12 years, the amount of e-waste generated per year worldwide almost doubled from 34 to 62 billion kg in 2022 (see Figure 28).[158]
E-waste is mainly generated by discarded large household appliances such as fridges, washing machines, ovens and dishwashers; small appliances such as microwaves, kettles, and toasters; IT and telecommunication equipment; lamps; screens and monitors; and photovoltaic panels. This amount is projected to increase to 82 billion kg by 2030.
Leading causes for this rapid increase are technological progress, increased consumption, limited repair options, short lifecycles and inadequate e-waste management infrastructure.
Manufacturing companies should apply design-out-waste principles and techniques to tackle the waste challenge during their products' design and production processes.

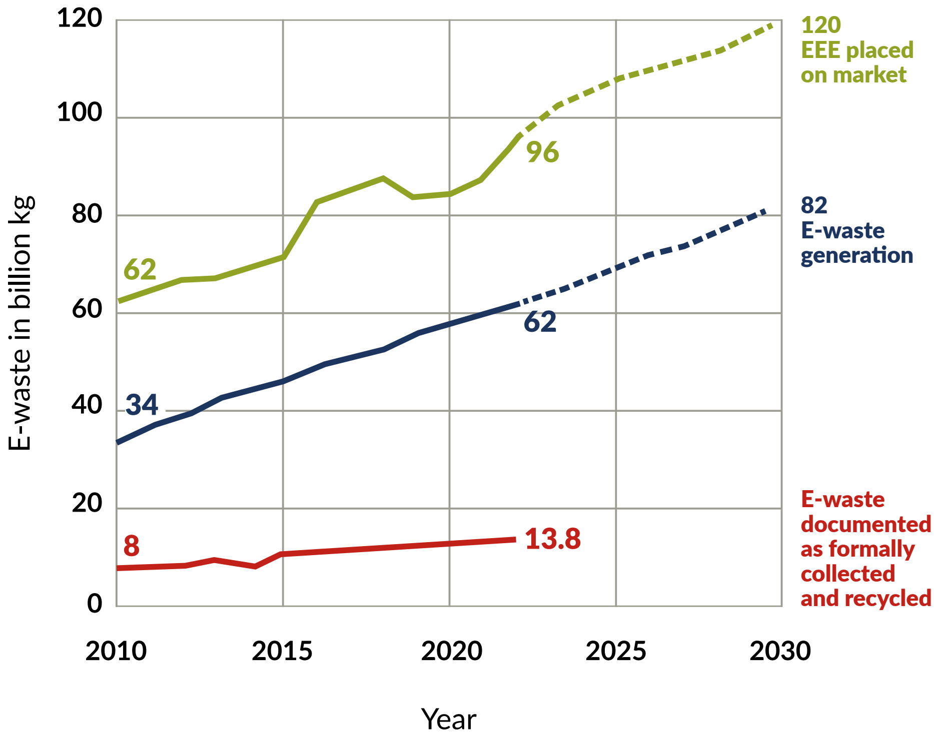


Figure 28

Projections of global e-waste generation[159]

3

Futureproofing the future of manufacturing

Geopolitical actions

Resilience is the key to navigating the increasingly volatile geopolitical landscape for manufacturing companies. Static value chains and manufacturing supply chains must become highly dynamic and adaptable to disruptions, including high-speed rapid reorchestrations and low recovery time after unforeseen changes and disruptions.

Drivers

The geopolitical landscape is becoming increasingly complex and uncertain. The number of challenges significantly and simultaneously affecting the world and the manufacturing sector is growing — the term polycrisis can adequately describe the current world situation.

The World Economic Forum has recently used the term "polycrisis" to explain the current world and the collective experience that everything is happening and having a significant impact.[160] A polycrisis denotes a situation where different crises interact, resulting in the overall effect exceeding the sum of each part to a great extent.[161]

In the Global Risk Report 2023, the World Economic Forum shows that the global risk landscape is highly interconnected. Thus, diverse risks and crises, such as climate change, the COVID-19 pandemic, armed conflicts, rising costs of living and energy, etc., are at significant risk of leading to an interconnected polycrisis.[162]

While nations and regions worldwide try to cope with these crises – sometimes in different ways and at different paces – the conditions and geopolitical landscape become highly uncertain for manufacturing companies. The current state of manufacturing is under the influence and pressure of several positive and negative drivers. First, the impacts of climate change are becoming more frequent and pronounced, creating related disasters and irreversible tipping points worldwide. Although climate change can directly affect geopolitics, these are rarely discussed or accounted for. Climate change impacts can lead to negative tipping points; for example, rising global temperatures have caused the melting of polar ice sheets, leading not only to natural disasters and financial crises but also impacting human societies at large – creating food and water insecurities, mass migrations, regional conflicts and the destabilisation of governments. Moreover, the rapid spread of the COVID-19 pandemic drove many countries to rethink their manufacturing strategies and undermined the vulnerabilities and dependencies between economies. An uneven distribution of global resources can lead to increased protectionism and isolation, diminishing international trade and industrial growth.

Multipolarity and the competition for influence and dominance are important current themes. Political instability in many regions, armed conflicts, sanctions, protectionist policies, and shifting policies and regulations across nations and regions are among the challenges and potential negative aspects for the manufacturing sector. On the flipside, increased international collaboration on sustainability goals, regulations to combat climate warming, and promoting responsible use and development of new technologies may positively impact manufacturing and create favourable conditions and opportunities.

Technological sovereignty is a crucial goal for nations seeking to maintain control over their technological development, reduce dependence on foreign sources, and increase economic independence. New technological advancements are utilised to be ahead of competitors. Recent technological breakthroughs have made it to market and disrupted existing business models. Examples are the widespread introduction of LLMs such as ChatGPT and the advancement of EUV lithography. Additionally, existing web technologies are continually changing traditional business models. These drivers have put pressure on the affected companies.

Pressures

Since 2016, geopolitical disruptions have increasingly impacted manufacturing supply chains and continue to put pressure on how they function. Brexit created uncertainty in business across the UK in terms of labour and material shortages, trade wars and corresponding reshoring strategies in the US did not necessarily favour local production, and the Covid-19 pandemic created global political instability, mistrust among policymakers and citizens, and led many nation states to adopt protectionism principles. Disruptions from COVID-19 led to increased and decreased consumer demand for specific products. For instance, increased demand for daily consumables as well as medical equipment put pressure on the production of such goods locally and a decrease in some imports and exports (and related transportation costs and petrochemical reliance). The global competition to develop vaccines intensified, putting immense pressure on manufacturing companies to come out on top. The 2022 Russia-Ukraine war has created an energy crisis in Europe. This, along with increased sanctions, has impacted the continuous or smooth operations of global supply chains and, specifically, the competitiveness of European industries.

Shifting regulatory landscapes, such as decarbonisation pressures from the Net-Zero Industry Act within the EU's Green Deal, pressure countries to create a solid manufacturing base with access to net-zero technologies and maintain relevant skills in the EU. This could create market fragmentation and competition due to varying access levels to green technologies and corresponding resources. In 2022, regionalisation or fragmentation of the global economy was mentioned as one of the top three geopolitical risks to industrial growth.[163] This has pressured manufacturing companies' strategic investments to improve their resilience to geopolitical threats and uncertainties.

Some other geopolitical disruptions worth mentioning that have put pressure on manufacturing are the disputes between China/Japan and China/Myanmar over rare-earth materials and semiconductor trade policies imposed by the US on China and South Korea's plans to compensate citizens for forced labour in Japan during World War II. All this has heightened tensions, placing additional pressure on the semiconductor industry. The strained diplomatic relations between the two nations, key global tech supply chain players, could disrupt critical partnerships and material sourcing. As the semiconductor industry relies heavily on smooth international cooperation, any escalation of historical disputes could impact production, trade agreements, and the overall stability of the sector.

The free flow of Internet traffic and global service offerings were taken for granted in the past. China was among the first countries to introduce comprehensive digital sovereignty in the early 2000s, also known as the "Great Firewall of China." With some years in between, many other nations, such as Iran, the UAE, and Turkey, followed President Xi's idea when he proclaimed in 2015: "We should respect the right of individual countries to choose their path of cyber-development independently". The EU did not block Internet traffic similarly but introduced policies such as the GDPR, the EU Data Act and the Digital Markets Act, making it impossible to offer services without fully complying with local laws.

State

The current state of global manufacturing systems includes uncertainty in manufacturing capacity, logistics, and supply. For instance, the prolonged Russia-Ukraine war has led to disruptions in trade and interrupted supply chain operations. Weaker demand for EU products in Russia or central Europe has increased regional price competition and energy supply imports. In addition to industrial complexity, manufacturing companies must keep up with the fast pace of changing regulations, sanctions and standards, which also differ in various countries. For instance, the scope of decarbonisation regulations varies in the EU, US, and Asia, but they share a common focus on achieving net-zero goals. For example, the EU Emissions Trading System (ETS) differs from the UK's. The latter's scope includes the shipping and energy sectors and different allowance levels. The EU has also introduced an import tax on carbon, which other countries are following closely. The varying pace of individual countries' decarbonisation efforts can delay reaching global climate-change targets.

The current state of digital global business opportunities is as fragmented as ever before. For instance, there are 17 different data protection laws. In addition, multiple other regulations, such as geo-blocking and payment restrictions, prohibit the free offering of digital services globally. The current state of cyberattack threats for manufacturing companies is daunting. About 25% of cyberattacks target manufacturing companies, exploiting over 260,000 known vulnerabilities.[164] Companies witnessing these ongoing attack attempts face this new standard and are constantly alert.

Manufacturing companies are currently operating in a VUCA world, one which is volatile, uncertain, complex and ambiguous. This trend became even more pronounced after the COVID-19 pandemic, as manufacturing industries now face ongoing challenges in increasingly unpredictable environments. The disruption of global supply chains, shifting demand patterns, and heightened uncertainty have forced manufacturers to adapt rapidly, with the potential for further unexpected changes continuing to shape the industry's landscape. As previously mentioned, fluctuations such as rapid changes in market demand, critical raw material availability and prices, and advancements in innovation and technology have made it complicated for manufacturing companies to strategically plan for and execute their operations optimised. Geopolitical events can add to this uncertainty, making decisions and risk assessment activities difficult. The inherent dependencies within complex global supply chains make their management highly challenging. Coordinating across multiple regions, suppliers, and processes increases the risk of disruption, complicating efforts to maintain efficiency, resilience, and reliability. Lastly, decision-makers may not have sufficient information about market conditions and current industrial states. Without data-driven insights and given the presence of ambiguous information related to the geopolitical situation, manufacturing decision-making can be severely affected.

Impacts

Cyberattacks are already having a high and increasing impact on manufacturing companies. From 2018 to 2023, 478 confirmed ransomware attacks on manufacturing companies were documented. The ransom demands ranged from US$5,000 to US$50 million. Manufacturing downtime varied from several hours to 76 days; the overall cost of downtime was estimated at US$46.2 billion.

Changed data policies impact IT system costs, migration efforts, and maintenance. Global IT systems had to be split into regional data sovereignty zones, and many cloud platform providers offered special sovereignty zones to comply with local regulations.

The impacts of geopolitical tensions, shifting regional and national alliances, trade wars, sanctions, natural disasters, etc., are significant for manufacturing companies and industries. Impacts include lower security in the supply of components and materials, longer lead times on supply, price fluctuations, and unexpected demand fluctuations. Various disruptive events, such as the COVID-19 pandemic, the war in Ukraine, and the blocking of the Suez Canal, also significantly changed demand and supply conditions for manufacturing worldwide. Such disruptions and unexpected events can cause impaired efficiency and competitiveness due to a lack of supply, increasing safety stocks, and reduced operations. While unstable, volatile and unpredictable demand and supply conditions are becoming the new normal for many manufacturing industries, unpreparedness to tackle these situations may lead to prolonged recovery time after disruptions and significantly impaired competitiveness.

Responses

Resilience is critical to respond to the drivers and pressures impacting the manufacturing sector. To enhance resilience in the face of geopolitical disruptions, manufacturing companies need to respond and build the right capabilities on all levels. From increasing flexibility and adaptability of manufacturing systems and internal operations, they are expanding the ability to rapidly orchestrate value chains based on changes in demand and supply conditions to developing dynamic resilience capabilities across the entire organisation.

Strategic-level responses: building dynamic resilience capabilities

Resilience against geopolitical threats can be designed into manufacturing organisations by building dynamic capabilities in three time-dependent stages of resilience: anticipation (when risks occur and could potentially become disruptions), coping (when disruptions occur) and adaptation (when organisations learn from disruptions so that they are avoided in the future).[165] Enhancing anticipation capabilities — such as situation awareness, visibility, and security — empowers manufacturing companies to sense and forecast potential geopolitical risks and corresponding disruptions proactively. These companies can better anticipate and address future challenges by sharing knowledge and information and improving transparency within their supply chains. Technologies such as digital twins can improve the real-time monitoring of supply chain shocks, digital platforms can enable end-to-end supply chain visibility and information sharing, and machine learning can create possible future scenarios where data is collected in real time from manufacturing to distribution.[166] Furthermore, investing in safety stocks or buffers (redundancy), for instance, moving from a just-in-time to a just-in-case approach, can help maintain backup sources of supply. These redundant sources, however, need to be balanced to prevent excess waste that could negatively contribute to sustainability outcomes or contribute to protectionism in the race to strengthen individual countries' resilience.

When geopolitical risks potentially disrupt manufacturing operations, companies should have sufficient coping capabilities such as agility, flexibility, collaboration and leadership to manage these disruptions. Flexibly reconfiguring and repurposing factory facilities in times of uncertainty and geopolitical crisis can prevent dependencies with geographically dispersed suppliers and ensure the competitiveness of local manufacturing. On the other hand, collaboration with other companies to create strategic alliances and coopetition opportunities can decrease uncertainty and positively drive joint efforts towards climate change. A robust cultural mindset from leadership to employ innovative technologies can prepare manufacturing companies to foresee and manage geopolitical impacts. Radical transformations and adaptation strategies are crucial after manufacturing companies are impacted by disruptions. This is a learning phase where companies continuously learn from disruptions and create better mitigation solutions for the future. Knowledge management capabilities, for instance, can help manufacturing companies act on previously generated knowledge (change management) or conduct upskilling, reskilling, and multi-skilling of new employees to avoid quick turnovers and related migration issues.

Despite the known unknowns related to geopolitical tensions and uncertainty, manufacturing companies should invest in contingency planning that involves manufacturing reconfiguration and comprehensive scenario planning, for instance, creating a wide range of possible futures involving geopolitical risks and opportunities. Knowledge of their market position, such as financial strength, market share, efficiency, and an inherent ability to absorb losses, will help them create autonomy for critical materials and goods.

Supply chain-level responses: Manufacturing as a Service (MaaS)

Manufacturing as a Service (MaaS) is a concept that can transform the manufacturing sector by providing dynamic and on-demand manufacturing capability and capacity – thereby increasing both the resilience and robustness of the manufacturing value chains.

MaaS can be described as a distributed production system where resources are offered as services, allowing manufacturers to access networked providers to implement their manufacturing processes.[167] While the concept of MaaS has gained significant relevance and attention in recent years, the idea is not new. Although many examples of MaaS are in action for simpler processes, making the concept work for any manufacturing process and across a significantly distributed number of manufacturing companies is a far more challenging and complex task with unknown and far-reaching potential.

MaaS is a new and transformative paradigm where manufacturers can overcome the challenges in traditionally static value chains and increase resilience. Such challenges include high risks and long recovery times when disruptions change demand-and-supply conditions. For instance, if the supply of specific critical components suddenly becomes unpredictable or impaired due to, for example, changing global trade agreements, interrupted logistics, the closing of factories, etc., the recovery capacity of a manufacturing company relies on the ability to either utilise an existing stock or find alternative new suppliers. Likewise, suppose changes in the volume and variety of product demand occur, for instance, because of new trade agreements, market expansions, or changing regulations. In that case, the ability of manufacturers to meet new demand and business opportunities relies heavily on the ability to rearrange existing manufacturing processes quickly, activate additional manufacturing capacity, and reorchestrate the entire value chain to meet new demand conditions. With static supply chains and traditional buyer and supplier relationships, the ability to respond quickly to such changes is largely impaired. To increase resilience, manufacturing companies must make decisions much more frequently and speedily regarding footprint design, where and how to invest in manufacturing capacity, which suppliers to engage with and use, and which logistics setups to use. This means that strategic manufacturing decisions need to be made much faster, immediately operational, and considered more frequently, with a much shorter time horizon.

With the basis of offering a large variety of manufacturing processes and capabilities as services, manufacturing companies can form relationships and orchestrate value chains on demand. On one side, the service provider (a manufacturer offering existing processes and manufacturing resources as services) will be able to increase capacity utilisation and broaden the pool of potential customers to engage with. On the other side, the service consumer (a manufacturing company that, for some reason, needs additional manufacturing capacity) will be able to connect to manufacturing processes and resources on demand, thereby increasing the ability to meet demand and supply changes without significant investments. Traditionally understood, the manufacturing service provider and consumer are different and perhaps geographically spread entities. However, large manufacturing enterprises with a global footprint will essentially be able to act both as providers and consumers considering the variety of locations, departments, and plants – internal and external manufacturing as a service concept. Therefore, manufacturing as a service holds excellent potential for large global manufacturing enterprises and SMEs to increase resilience through a more networked and connected mode of operation.

The benefits of manufacturing as a service include increased resilience and sustainability. Servitising manufacturing processes, resources, and assets and offering these internally and externally will enable manufacturers to dynamically orchestrate and reorchestrate supply chains and value networks based on volatile and dynamic conditions, such as disruptions, new opportunities, and unexpected events.

Thus, previous strategic and long-term decisions related to production network building, supplier collaboration, factory building, etc., will be made operational and can be done efficiently and quickly on a shorter-term basis. In this way, companies will be able to qualify and connect with new suppliers more quickly, diversify and enlarge the supplier base significantly, increase the use of manufacturing resources and capacity, improve the ability to meet new market opportunities, meet local content requirements, localise manufacturing activities, mitigate risks and reduce the time for recovering after a disruption to demand or supply.

The foundation for making manufacturing as a service work is extensive. Mainly, there is a need for highly adaptable, reconfigurable, and flexible manufacturing systems and processes that can be offered as a services; software, platforms and technologies for connecting manufacturing companies and matching the manufacturing as a service providers and consumers; new models, simulations, digital twins, and planning technologies; and new ways of sharing and accessing data across companies including the willingness of companies to engage in larger networked systems with potential cross-company and country regulatory barriers.

Operational-level responses: internal flexibility

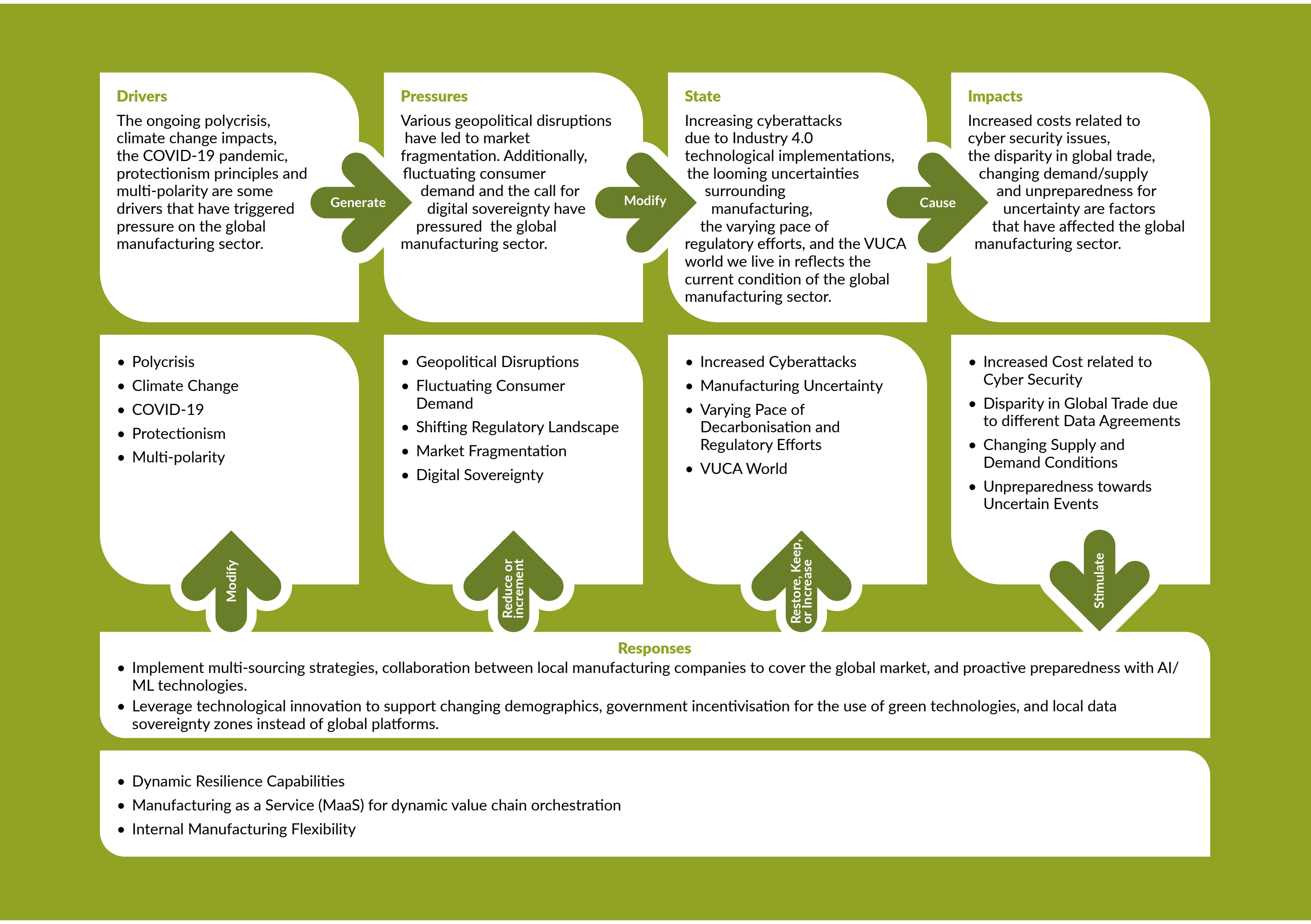
Internal manufacturing flexibility refers to the ability of an in-house manufacturing system to adapt to changes in the production environment, including variations in product types, production volumes, and market demands. This adaptability is essential for manufacturing companies to react to market changes and supply chain disruptions. Manufacturing flexibility can be grouped into the following sub-categories:

- *Machine flexibility* – the ability of machines to perform a range of operations or produce different products with minimal downtime or reconfiguration.
- *Routing flexibility* – the capacity to alter the sequence of operations or the product flow through the manufacturing process, allowing adjustments based on current production needs.
- *Volume flexibility* – the ability to scale production up or down in response to changes in demand without incurring excessive costs.
- *Product flexibility* – the ease with which a manufacturing system can introduce new products or modify existing ones to adapt to changes in consumer preferences or market trends.

- *Process flexibility* – the capability to employ various production processes for manufacturing a product, optimising production efficiency.
- *Expansion flexibility* – the potential to increase production capacity to meet rising demand without significant investment in new machinery or equipment.
- *Operational flexibility* – the overall agility of the manufacturing system, including its capacity.[168, 169, 170]

Manufacturing flexibility is crucial for companies that face fluctuating demand. It enables them to stay competitive and responsive to market disruptions. This flexibility can be achieved by introducing reconfigurable manufacturing cells with exchangeable tools and fixtures, allowing various products to change quickly over time. In parallel or as separate sequential processes, these cells might have higher initial investments than conventional lines but offer higher flexibility. In the context of increased uncertainty, the trade-off between cells with a short ROI and more expensive cells with more excellent flexibility corridors must be considered. Therefore, the investment decision must consider the changed business conditions.

By tackling these three interrelated actions, building dynamic resilience capabilities on a strategic level, using manufacturing-as-a-service to increase the resilience of the value chain, and increasing flexibility and reconfigurability on an operational level, manufacturers can improve their ability to respond to disruptions, reduce costs, and maintain operational continuity.



Economic actions

The global manufacturing sector faces several significant economic challenges, showing the need to reinforce its industries' agility and resilience.

Drivers

Crisis. The COVID-19 pandemic brought an unprecedented shock to global manufacturing due to mobility restrictions and shutdowns of factories, resulting in international supply chain disruptions.[171] Regarding the dependency on the complex structure of supply chains within and across countries, a disruption in one part of the supply network can influence the global production process. In addition, the COVID-19 situation complicated customer habits and caused demand peaks in some businesses, such as healthcare products and electronic devices.[172, 173] This crisis awakened the manufacturing sector to keep its eyes open for exogenous events; for example, extreme climate-related events (flood) and geopolitical developments (Russia-Ukraine conflict) could influence the functioning of supply chains and cause disruptions along regional and global supply chains.

Geopolitical uncertainty. Rising tensions relating to wars in Europe and the Middle East and escalating US-China competition have created significant manufacturing risks, especially for businesses operating internationally. In addition, over 60 countries will hold national elections, involving nearly half of the world's population voting in 2024, which could lead to a shift in leadership and policy. Business leaders cannot ignore political uncertainty against an evolving global order.[174] One of the most significant issues manufacturing confronts is "How can global manufacturing remain in geopolitical uncertainty?" The cost of moving in the wrong direction is a risk to assets, growth, value creation, and people. On the contrary, there is a real advantage in building a systematic approach called geopolitical resilience.

Digital Revolution. Manufacturing is encountering scalability, mass customisation, and interoperability challenges, and new technologies continue to emerge.[175] Incorporating IoT, robotics, and analytics can enable organisations to react quickly, improving company performance and customer satisfaction. The digitally connected ecosystem and real-time visibility assist in the removal of silos across the sectors while adding information transparency in supply chains, responding to customer needs quickly, and cooperating with partners to strengthen trust.[176] Even though integrating technology into manufacturing provides opportunities for manufacturers to design innovative products and bring them to market faster, it has been controversial because of its detrimental effects on job displacement and energy conservation. Therefore, the issue of human-centric technologies should be considered.[177]

Pressures

Inflation

In recent years, global manufacturing has faced significant inflation caused by labour shortages, supply chain disruption, and volatile input costs. The research found that input costs reached their highest levels in 2022, squeezing profit margins among food and beauty consumer packaged goods companies.[178] Even though the inflation rate is easing, central banks have indicated that they will hold interest rates steady or cut them very slowly.[179] Consequently, buyers will become increasingly willing to accept price increases, even if higher input costs are justified, leading to strong demand and low manufacturing activity. Finding the right balance between price and volume is a massive challenge for manufacturing. This can affect players who react slowly to return margin positions to levels seen before the inflation spike. Therefore, proactive strategies should be addressed when evaluating and adjusting pricing strategies.

Labour shortages

For almost two decades, labour markets across advanced economies have tightened, a phenomenon that continued with the pandemic and a long-term trend that may continue as workforces age and population growth decelerates.[180] Job vacancies have climbed steeply in sectors such as healthcare (pandemics) and hospitality (ageing society), as well as those with stagnant productivity, like construction (recovery after the pandemic).[181] This pressure presents both challenges and opportunities. For example, jobseekers may find work more efficiently and may get higher wages. Yet upward wage pressures spur inflation and stress businesses, as companies may need to turn down orders because they cannot hire enough workers to satisfy demand. Without action, labour shortages may continue to hit sectors that struggle to increase productivity. Manufacturing must consider productivity and find new ways to expand the workforce by focusing on skilling and reskilling, offering more flexible work, and internal mobility.

Innovation

With global dynamics in flux, companies have faced significant changes, ranging from evolving customer requirements to demand fluctuations and complex planning systems. Innovation helps manufacturers pursue growth opportunities and effectively compete in the ever-evolving market while navigating volatility and uncertainty.

Developing new products and services enables manufacturers to meet the changing needs of customers and markets while streamlining production processes and reducing costs. Thus, modern manufacturers are pressured to hasten their product/process innovation through digital transformations and Industry 4.0 technologies focusing on agility, resilience, and customer-centricity.

State

Outdated manufacturing business and operational models and deficiency in innovation in SMEs

Due to rapid technological advancements, traditional business and operating models must be updated. According to the European Commission, enterprises with fewer than 250 employees and an annual turnover of less than €50 million are classified as Small and Medium-sized Enterprises (SMEs). Due to limited financial resources and a knowledge gap regarding the benefits of new technologies, SMEs' investments in innovation are constrained. As a result, SMEs often struggle with outdated business practices and operational strategies, which can impede their ability to adapt to changing market conditions.

The ongoing increase in energy consumption in the manufacturing sector

According to the US Energy Information Administration, the industrial sector consumes more delivered energy than any other end-use sector, accounting for approximately 54% of the world's total delivered energy. The United Nations Industrial Development Organization estimates that industrial energy use will grow between 1.8% and 3.1% annually over the next 25 years. This increasing state of energy consumption highlights the need to shift towards only renewable energy, which presents challenges and opportunities. Green energy investments can offer competitive advantages and help stabilise the volatility of energy costs.

The current state of the global manufacturing sector after all these pressures

The manufacturing sector continues to face significant challenges. 2024 manufacturers are expected to grapple with economic uncertainty, ongoing skilled labour shortages, persistent supply chain disruptions, and new pressures to innovate products to meet net-zero emissions targets. Technology is set to play a crucial role in helping manufacturers navigate these hurdles. Despite the challenging business environment and some companies considering pausing investments, many manufacturers remain focused on digital transformation, prioritising efficiency and organisational resilience. They are increasingly adopting smart factory approaches, exploring the industrial metaverse, and leveraging new technologies like generative AI to enhance operations and add value.[182]

Impacts

Production interruption of raw material

Global supply shortages have been driven by several factors, including production halts during the coronavirus pandemic, disruptions of international transport routes, such as the Suez Canal blockage by a container ship in March 2021, and war-related trade disruptions following Russia's attack on Ukraine, which further blocked shipping routes. These crises have caused significant delays in delivering raw materials and components abroad.

When production ceases in a supplier country, it reduces the global supply of affected components and raw materials, leading to supply shortages and subsequent price increases. This raises production costs for companies reliant on these inputs, resulting in higher consumer prices. Manufacturing businesses have been brutally hit, as the unavailability of raw materials severely disrupts supply chain management, causing significant losses in output and revenue. The scarcity of raw materials is the most frequent cause of disruptions in the manufacturing supply chain, substantially impacting production rates, increasing costs, and diminishing customer satisfaction.

Increased labour costs

Rising inflation has led to a higher cost of living, causing workers to demand increased wages to sustain their standard of living. This poses a significant challenge for manufacturers under growing pressure to raise wages. If manufacturers do not meet these demands, they face the risk of labour unrest and potential work stoppages, which could halt the production of goods and services. Despite the additional financial burden, many manufacturing companies have been forced to raise employee wages to prevent such disruptions. This adjustment aims to maintain production continuity and satisfy market demand, highlighting the impact of increased labour costs driven by inflation.

Product innovation and process innovation

Innovation pressure in the global manufacturing sector has led to significant positive impacts, with product and process innovation standing out as key drivers of competitive advantage.

Product innovation involves developing new products from novel materials or enhancing existing products to better satisfy customer needs. This type of innovation can open new markets or better serve existing ones, making it a crucial source of competitive edge for firms. By improving product quality, product innovation boosts overall firm performance and strengthens market positioning.

Process innovation, in contrast, focuses on reengineering and enhancing internal business operations. It spans various functions, including technical design, R&D, manufacturing, management, and commercial activities. Process innovation involves developing new or improved techniques, systems, and procedures to transform inputs into outputs through technological advancements, skill development, and operational improvements. For the manufacturing sector, process innovation is critical and should be emphasised as a core competency for gaining a competitive advantage. It is closely linked to firm growth and is essential for sustainable success.

Responses

Business Continuity Management

Business Continuity Management (BCM) is a comprehensive management process designed to identify potential organisational threats and assess their impact on business operations. It establishes a framework for building organisational resilience. It provides the capability for an effective response that protects the interests of key stakeholders and the organisation's reputation, brand, and value-creating activities.

BCM integrates various disciplines, including Emergency Response, Crisis Management, Disaster Recovery (technology continuity), and Business Continuity (organisational and operational relocation). According to the Business Continuity Institute (BCI), BCM's primary goal is to safeguard the organisation against potential disruptions by ensuring it can effectively respond to and recover from events, minimising the impact on customers, clients, and overall operations.

Digital-twins technology

Manufacturers worldwide face significant pressure to meet demand in an environment marked by resource constraints, talent shortages, and ongoing supply chain disruptions. In response to these challenges, digital twins are gaining prominence as a leading technology, enabling manufacturers to quickly scale capacity, enhance resilience, and optimise operational efficiency.

A digital twin is a virtual replica of a system's behaviour within its operating environment, from a single product to a complex manufacturing process or an entire supply chain. This replica consists of a collection of digital models that simulate the system by processing and responding to data from its external environment. By integrating various models and data sources, digital twins offer a more accurate representation of real-world objects than traditional simulations.

Companies and digital-twin pioneers invest in this technology for several key reasons:

- *Risk-free product development* – Digital twins offer a safe environment for product development, allowing design and engineering teams to explore numerous design options without incurring the costs of physical prototyping and testing.
- *Enhanced testing and validation* – Digital twins enable the testing of new solutions across realistic scenarios, including rare and extreme conditions, improving the overall validation process.
- *Deeper insights into product behaviour* – By monitoring digital twins, engineers can gain real-time insights into any part of the system, helping them understand complex interactions and the behaviour of various product elements.
- *Data-driven product improvement* – Digital twins use real-world data to simulate the effects of proposed design changes, allowing companies to refine products based on insights from their performance in the field.

In manufacturing, digital twins are primarily used through virtual simulation models to create precise, solid models applied to product processing and assembly, ensuring accurate and efficient production control.

Effective knowledge transfer

Effective knowledge transfer is essential to tackle labour shortages. This can be achieved through structured mentoring programmes, where experienced employees share their expertise with newcomers. Complementing this with tutorials or digitised training manuals makes information more accessible. Implementing knowledge management frameworks that track the knowledge lifecycle, from creation to sharing and valorisation, is particularly crucial in the manufacturing sector, where managing operational knowledge effectively is vital. These approaches help preserve the company's skills and expertise.

According to the knowledge-based view, knowledge significantly impacts a firm's competitiveness. The transfer of best practices involves replicating superior internal processes across the organisation, which are proven to outperform other internal and external practices. This process encompasses the routine use of knowledge, the tacit knowledge of individuals, and collaborative arrangements within the organisation.

Best-practice transfer occurs when both a need and the knowledge to address that need exist within the organisation. Knowledge transfer also plays a vital role in driving innovation, which provides firms with a competitive edge and enables them to survive, grow, and thrive.

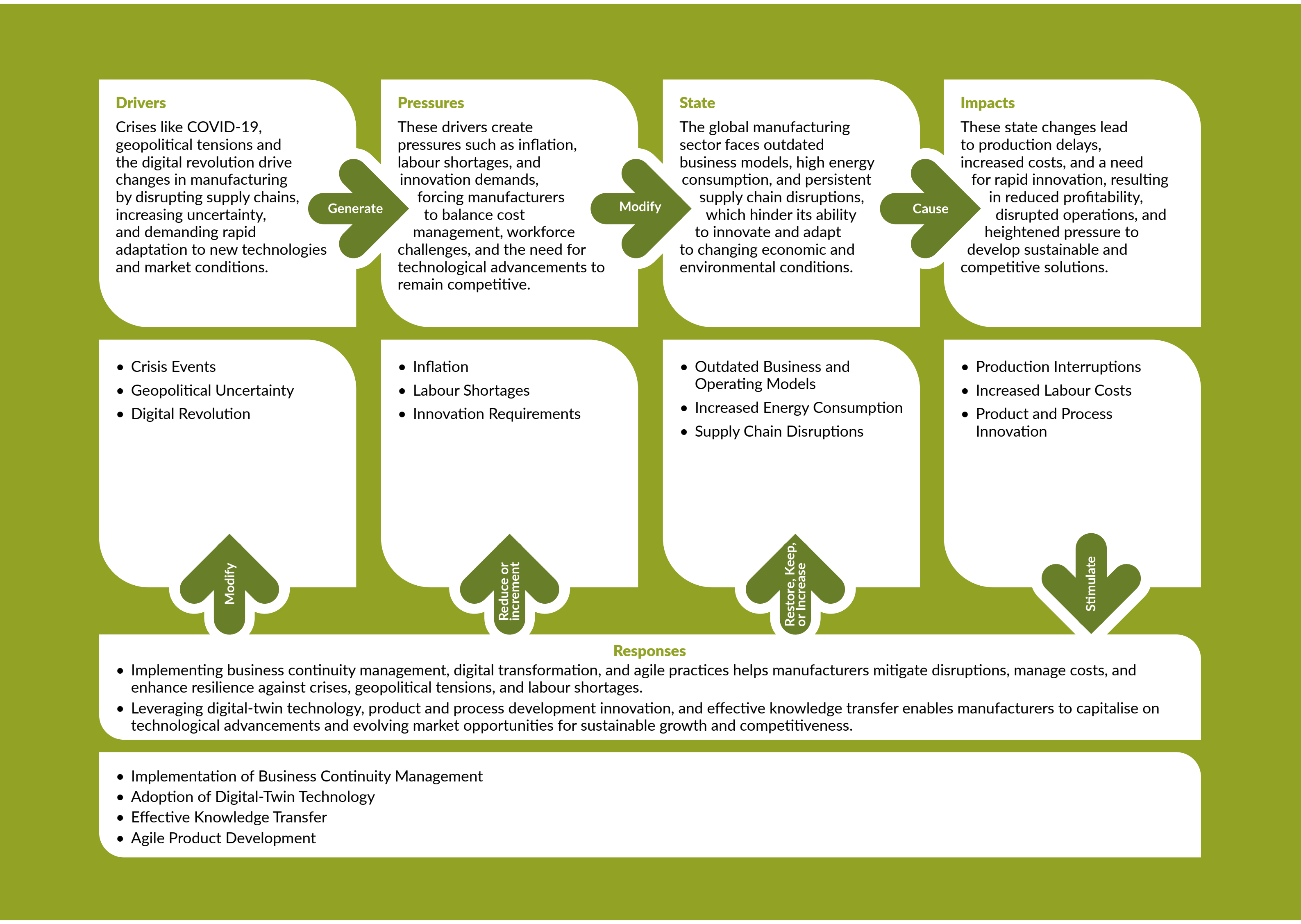
Agile product development

Agile manufacturing has emerged as a leading approach to maximise and increase the positive impacts of product and process innovation. Agile is a work methodology that leverages change as a competitive advantage rather than viewing it as a drawback. It achieves this through rapid learning, quick decision-making cycles, and utilising networks of teams within a people-centred culture. Agile is not limited to software development; it applies to hardware product development and complex systems that integrate hardware and embedded software, such as autopilot and infotainment systems in the aerospace, automotive, and consumer electronics industries.

Agile Transformation in the manufacturing sector requires a significant mindset shift, making the process comprehensive and iterative. It is comprehensive because it impacts nearly all aspects of the business and iterative because it demands constant adaptability in working methods.

Agile for hardware product development maintains the core principles of agile software (flexibility, evolution, and iteration) but must be specifically tailored to accommodate the unique nature of hardware products and the business environment. To successfully implement agile, leaders and managers should focus on five key areas: strategy, structure, process, people, and technology.

The strategic implementation of these responses shields companies from immediate disruptions and provides long-term economic benefits. These include reduced costs, enhanced operational efficiency, and sustained competitive advantages, all of which contribute to more robust financial performance and resilience in an increasingly volatile business environment.



Social actions

As the manufacturing sector undergoes significant shifts, the social dimension of these changes plays a crucial role in shaping the future of its workforce.

Drivers

We have identified three major societal drivers that will reshape global manufacturing. The first is the growth of prosperity and its impact on social demographics, driven by the overall economic development of nations. The second driver is regulatory shifts to improve working conditions, a key policy issue in many countries. Lastly, consumer behaviour is critical, driven by evolving market conditions and increasing demand for ethical practices.

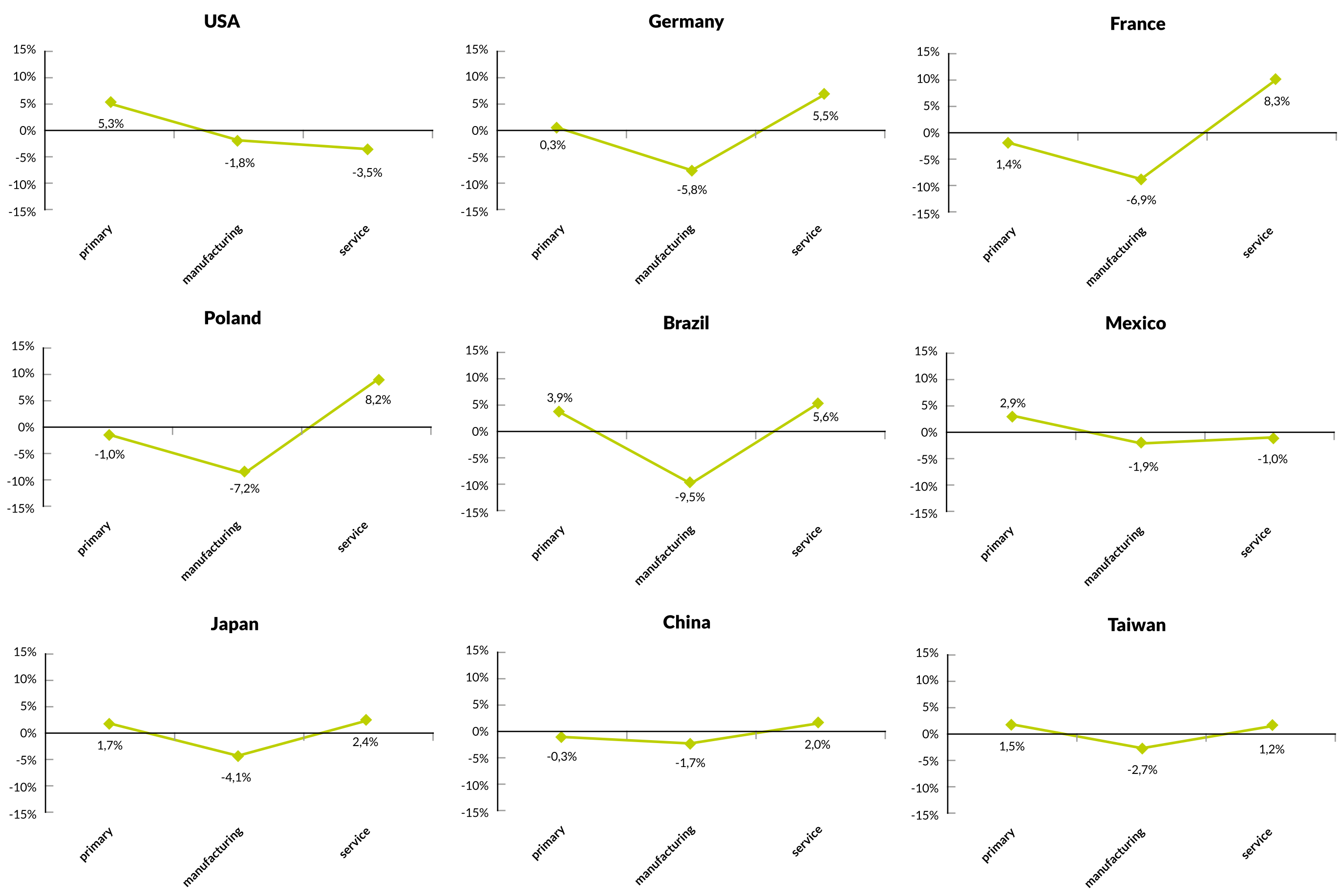
Prosperity growth and its impact on social demographics

Pursuing global prosperity is a key factor shaping the social context of manufacturing. As countries achieve higher levels of prosperity, interest in manufacturing declines. At the same time, service-related industries expand, as illustrated by the smiling curve in Figure 29.[183] This shift significantly changes workforce demographics. Workers become more urbanised and seek jobs less associated with manual labour. Additionally, as prosperity grows, fertility rates tend to decline, creating challenges for workforce renewal. Younger generations are less attracted to traditional manufacturing roles, driving a significant transformation in the sector. Moreover, rising prosperity is associated with increased environmental and social sustainability awareness, shifting consumer behaviour towards greener products and companies committed to environmental issues and diversity, equity, and inclusion initiatives.

Figure 29

Smile curve by nation using the World Input-Output Database, 1995–2011

(Source: Baldwin & Ito, 2022)



However, prosperity growth is only uniform across some countries. Many nations have been left behind. As evidenced by World Bank data (see Figure 30)[184], shared prosperity shows significant disparities across regions, with many low-income countries lacking available data. This indicates that social challenges for workers remain a substantial obstacle in achieving sustainable manufacturing for the future in these regions.

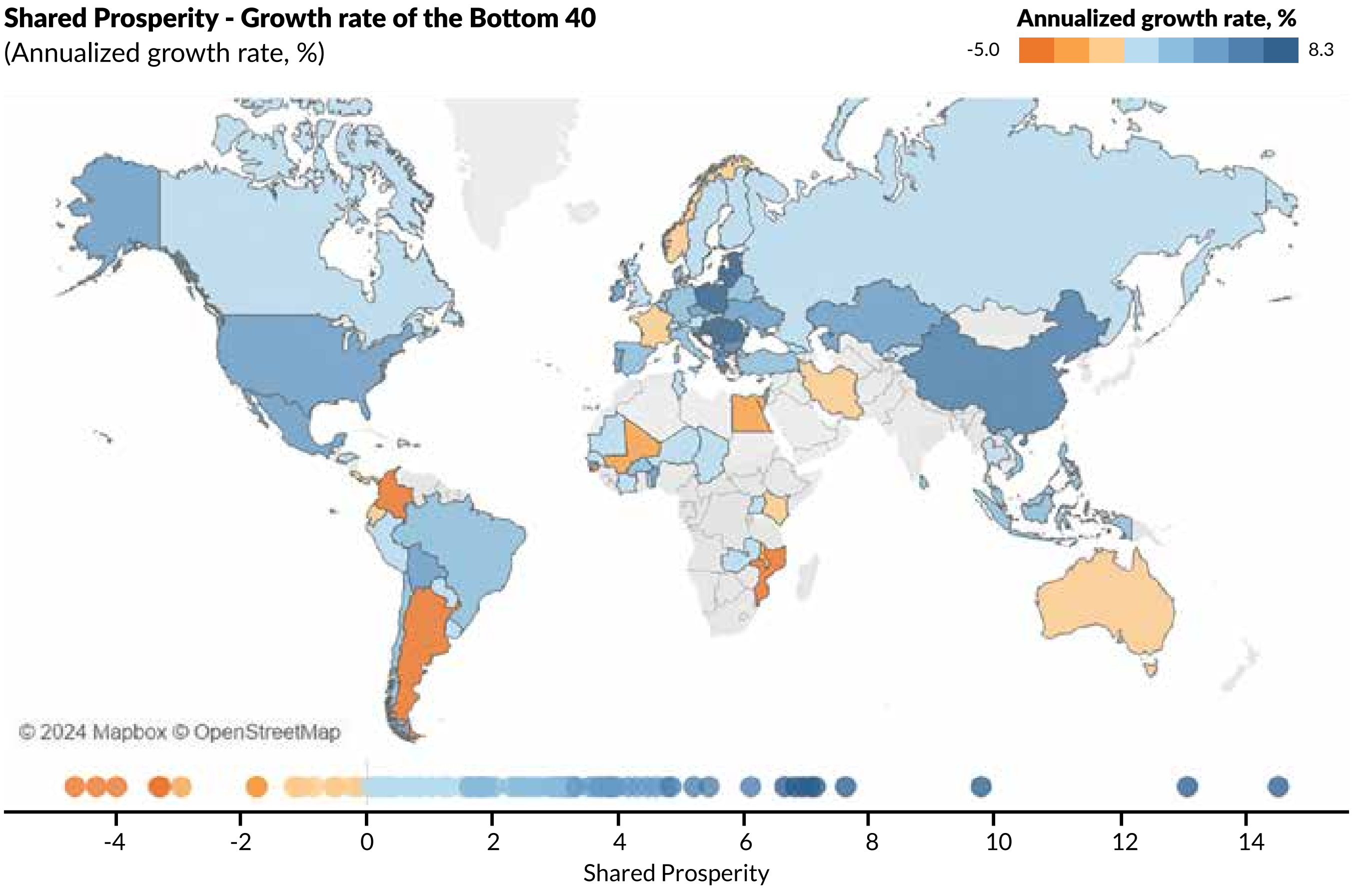


Figure 30

Shared prosperity worldwide

(Source: World Bank, 2024)

Regulatory shifts for improved workforce conditions

Governments and international organisations increasingly impose stricter regulations on environmental sustainability and labour practices, particularly in combatting modern slavery and improving workforce conditions. This is driven by the need to address the still alarmingly high number of workers subjected to modern slavery worldwide, as reported by the International Labour Organization (see Figure 31).[185] For instance, laws such as the UK Modern Slavery Act and the EU's proposed mandatory due diligence legislation require companies to ensure that their supply chains are free from forced labour, human trafficking, and other exploitative practices. The European Union's Green Deal, while primarily focused on environmental objectives, also underscores the importance of responsible labour practices as part of sustainable operations. Compliance with these regulations is essential for manufacturers to avoid legal repercussions and meet rising consumer demands for ethical labour standards and transparency throughout the supply chain.

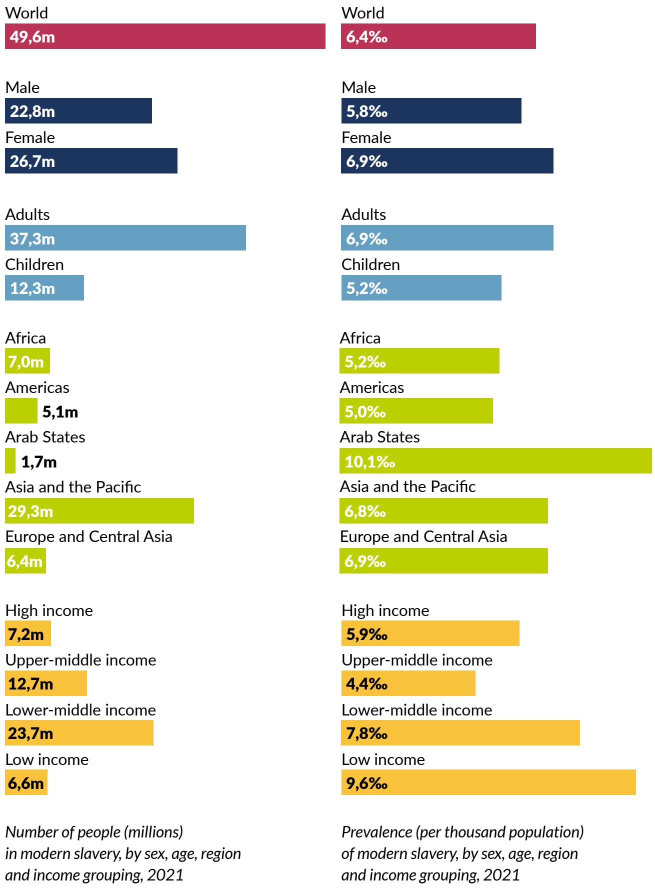


Figure 31

People in modern slavery worldwide

(Source: ILO, 2022)

Changing consumer expectations

Consumers today are increasingly concerned with the ethical and sustainable practices of the brands, products, and services they support. This rising demand for corporate responsibility extends beyond environmental issues, including how manufacturers treat their workers, focusing on fair labour practices and safe working conditions. As a result, manufacturers must align their operations with these consumer values to strengthen brand loyalty and maintain market relevance. Additionally, technology and social media have become powerful tools that influence consumer behaviour, making it essential for manufacturers to stay attuned to this more informed and socially conscious customer base.

Pressures

The above drivers exert significant pressure on the manufacturing sector, requiring new strategies and actions. One key challenge for manufacturers is the generational transition problem. As experienced, high-skilled workers retire, there is a risk of losing valuable knowledge during the renewal and transition to a new workforce. The knowledge concern is highlighted in recent research by the Manufacturing Institute's Center for Manufacturing Research, in collaboration with the Alfred P. Sloan Foundation: 97% of surveyed companies in the US expressed fears of losing essential manufacturing knowledge as older workers retire, intensified by the decreasing renewal of the labour force.[186] Also, a recent National Association of Manufacturers (NAM) survey found that nearly three-quarters of manufacturing executives consider attracting and retaining a high-quality workforce their top business challenge due to this critical context of skills gaps.[187]

A second pressure related to demographics is derived from the new generation's profile and lack of interest in pursuing careers in manufacturing.[188] A study of UK manufacturers reveals that the average age of workers in the sector has risen to over 40 years, a trend that concerns 75% of manufacturers. Research on Generation Z indicates that more than half of respondents are not interested in frontline manufacturing roles, with around 30% perceiving such work as "low-skilled, manual labour," which does not align with their career aspirations.[189] As a result, the manufacturing sector faces pressures to attract and retain new workers, leading to higher turnover rates. The declining interest among younger people in manufacturing creates a generational challenge that impacts the industry's labour-intensive activities and the accumulation of workforce experience.

New regulations, particularly those concerning workforce conditions, put pressure on companies to increase transparency about how their workers are treated and how they carry out their activities. While this drives positive change by improving worker wellbeing and ensuring that suppliers are equally committed to ethical practices, it also creates challenges, particularly for accessing suppliers and low-cost manufacturing options. Not all suppliers can meet the required levels of transparency and legal compliance. As a result, manufacturers are under pressure to develop their supply chains further or redefine them to ensure that good working conditions are upheld.

On the other hand, evolving consumer behaviour and social values regarding sustainability are creating positive pressure on global manufacturing. The growing demand for manufacturers to comply with ESG standards — measuring environmental, social, and governance impact — drives greater transparency and compels companies to adopt more sustainable practices.[190] With these new standards, manufacturing companies have higher pressure on their market operations. The responsibility over products and how manufacturers develop new products to meet sustainable requirements are also important, resulting in pressure from this new ESG context. This is a market expectation and economic pressure since the global ESG investing market is projected to grow at a CAGR of 18.8% from 2024 to 2030,[191] as shown in Figure 32.

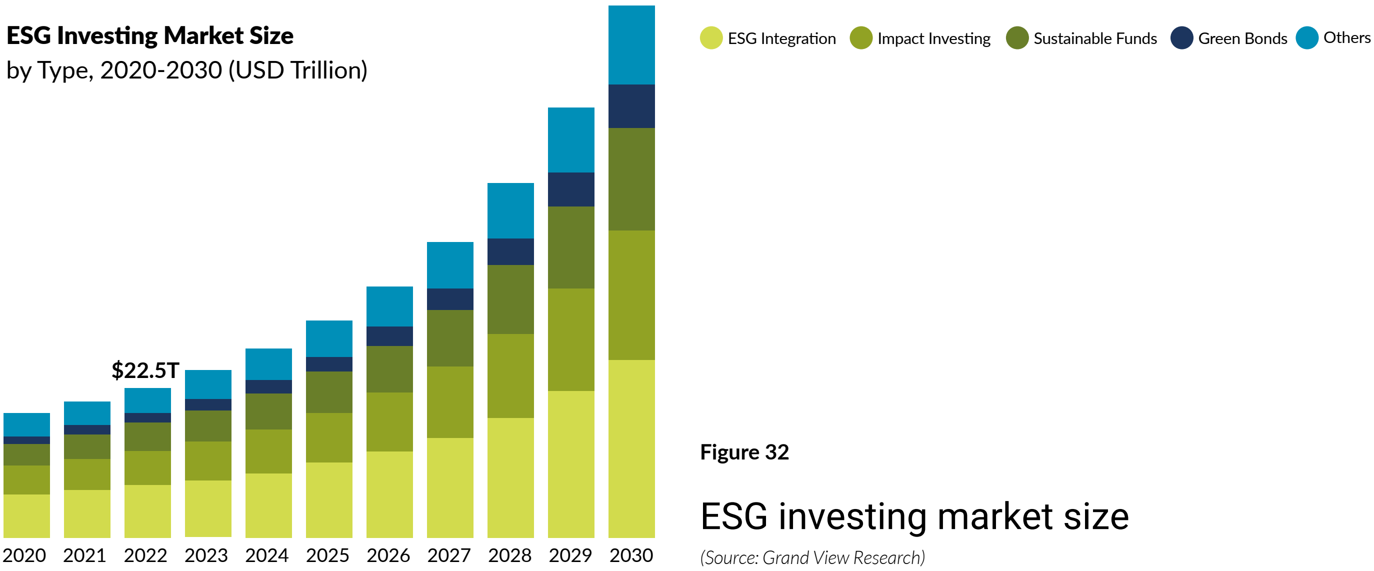


Figure 32

ESG investing market size

(Source: Grand View Research)

State

The described pressures modify the state and condition of the global manufacturing ecosystem. We identify significant states related to the previously described pressures.
Firstly, generational problems originating from demographic changes create a growing skills gap among manufacturing workers. Manufacturing employees must change 40% of their skills in the next few years. Some of the increasingly relevant skills are leadership and social influence, AI and big data, analytical thinking, creative thinking, environmental stewardship, and resilience.
Second, the manufacturing sector has stagnated despite global efforts to adopt sustainable practices and digital technologies. The reasons for this are twofold. First, the skills mentioned above are necessary for the industry to leverage green transformation and technological development fully.[192] Second, the limited diversity in terms of gender, ethnicity, and educational backgrounds restricts the innovation capacity of the workforce. According to the International Labour Organization, companies with more excellent gender balance experience increased creativity, innovation, and openness.[193] The lack of such balance in manufacturing may lead to stagnating organisational innovation, representing a driver. Also, homogeneous work environments need to be more inclusive, which can decrease employee retention, particularly among younger workers. Many companies still rely on hierarchical structures, limiting the adaptability to change. However, new business structures could introduce agility, workforce empowerment, and social responsibility alongside traditional business structures.[194] One approach the manufacturing sector has taken to address demographic challenges is the increased adoption of technology as a substitute for labour. Over the past few decades, automation has advanced significantly within the industry, leading to widespread job losses globally (see Figure 33).

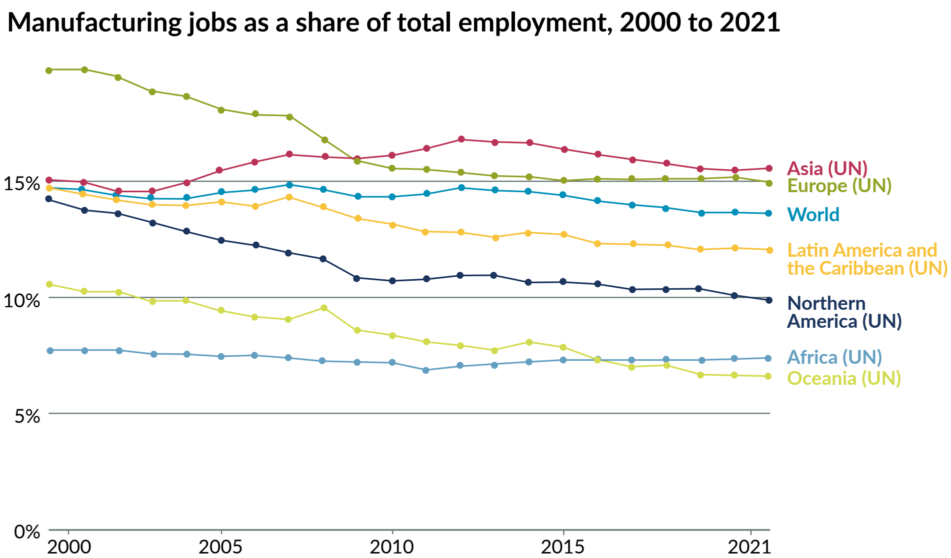


Figure 33

Manufacturing jobs worldwide

(Source: Our World in Data)

However, this shift towards automation presents a critical juncture for manufacturing, as it reduces the sector's flexibility to respond to significant changes in market dynamics. Workers, in contrast, have proven to be highly resilient and adaptable, as evidenced during the COVID-19 pandemic, when companies had to adjust their manufacturing systems rapidly. While automation can reach a point where the recovery of jobs in manufacturing becomes irreversible, potentially diminishing companies' capacity to pivot quickly, a resilient and adaptive workforce remains a crucial factor for the sustainability of the sector.

Impacts

The drivers, pressures, and conditions affect the manufacturing sector in three primary outcomes: manufacturing productivity, adaptability and innovation, and employee commitment and wellbeing.

Manufacturing productivity

The loss of knowledge due to the lack of workforce renewal and resulting skills gaps affects manufacturing productivity. In both developed and developing countries, the workforce is ageing rapidly, ending the era of abundant labour that fuelled economic growth in past decades.[195] While more people are working into their 60s and beyond, this is unlikely to offset the negative impact of an ageing population, as productivity declines with advancing age. Additionally, younger generations are less interested in manufacturing careers, leading to higher turnover rates among new workers. This high turnover among younger workers prevents them from advancing beyond the early stages of their learning curves, further exacerbating the challenge of achieving higher productivity levels.

Adaptability and innovation

A homogenous and less competitive workforce negatively impacts adaptability to changing contexts and stifles innovation capacity. A Deloitte study shows that increased diversity introduces new knowledge and perspectives, both crucial for driving innovation and problem-solving.[196] The loss of opportunities due to a lack of diversity has been highlighted in recent research, which demonstrates how much companies stand to gain by prioritising diversity. For example, a survey conducted by BCG of 1,700 companies across various countries — including Austria, Brazil, China, France, Germany, India, Switzerland, and the US — revealed that organisations with above-average diversity in their leadership teams experience greater returns from innovation and higher EBIT margins (see Figure 34).[197] Additionally, a diverse workforce enhances a company's ability to understand consumer behaviour and social values, enabling it to deliver products that are better aligned with market expectations.

Employee engagement and wellbeing

Lastly, companies focusing on new business structures that are concerned with social issues can positively impact employee commitment and wellbeing. For instance, the 2022 Gallup report showed that employees who feel included are more engaged. Furthermore, new working models featuring more flexible time schedules, a greater emphasis on workers' personal needs, and remote work options are emerging as critical demands. These changes aim to improve time management between personal and professional life, directly impacting employee engagement and wellbeing.

Responses

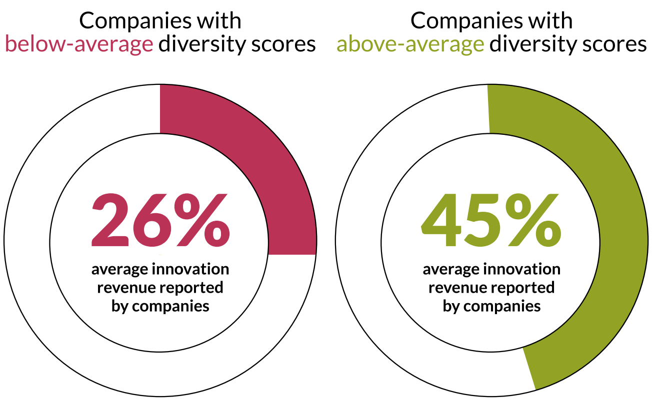
In light of the social challenges for the manufacturing sector, three critical responses have emerged to address the workforce's and society's evolving needs: adopting human-centric manufacturing practices, a commitment to worker education and upskilling, and implementing DEI initiatives. These strategies are essential for a more adaptable, innovative, and socially responsible manufacturing sector.

As part of the Industry 5.0 vision, human-centricity highlights the necessity for actions that put human requirements at the centre of industrial development to meet business needs and create decent work, enjoyable work environments, and the workforce's wellbeing.[198] Therefore, the industry calls for action to support human-centric manufacturing systems. These systems should be designed to handle the demographic shift and a smaller workforce. Moreover, these systems should focus on the wellbeing of every individual. This includes stress prevention, mitigating the risk of diseases, flexible work arrangements, and creating work cultures promoting work-life balance. Workers should be part of the decision-making process for technology implementation and be

Figure 34

Companies and diversity

(Source: BCG, 2018)

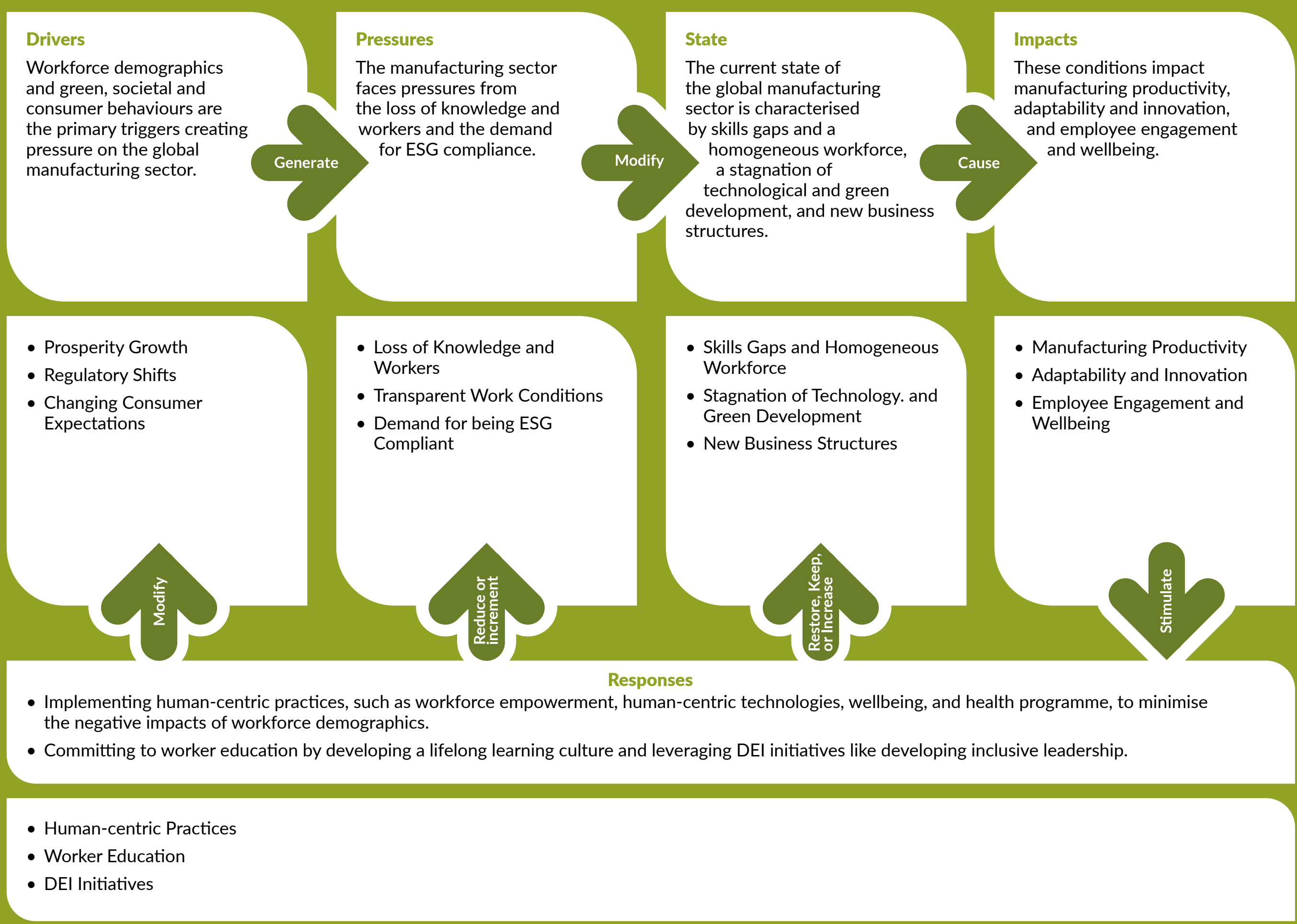


allowed to bring their values, needs, and ideas into the technology design and deployment.

Second, industrial leaders should emphasise workforce education and commit to their employees' learning and personal development. To achieve that, employers must invest in the support systems needed to understand and measure skills gaps and give their employees the resources to upskill themselves. In addition, employees need to develop a growth mindset and lifelong learning, while this requires leaders to create a culture of curiosity and openness. More than half of global CEOs are scared that skills shortages will significantly impact profitability in their industry over the next ten years.[199] However, manufacturing leaders will have to balance internal training with external hiring despite the difficulties due to the demographic trends. Therefore, when hiring and developing talent, managers should focus on the skills of their workforce, rather than only on diplomas. Thus, the manufacturing sector opens up to more potential candidates and can work more practically to develop the skills of their workforce.

Lastly, manufacturers have both a business and a moral imperative to go beyond and advance DEI initiatives. For this purpose, many responses can be implemented. Here, we have highlighted six critical actions to foster diversity, equity, and inclusion in a manufacturing sector: (i) Expand Diversity Definitions – include diverse cognitive styles and physical needs to foster a more inclusive environment; (ii) Create an inclusive culture – create a supportive culture where employees can be their authentic selves, encouraging open dialogue and diverse perspectives; (iii) Address equity across the workforce – ensure equity in all areas, including career development, compensation, and promotions; (iv) Develop inclusive leadership – build leaders who embody essential traits such as commitment, courage, bias awareness, curiosity, cultural intelligence, and collaboration; (v) Facilitate behavioural change and enhance accountability – implement actions to drive behavioural change, ensuring transparency of DEI efforts and results and, (vi) Walk the talk – demonstrate genuine commitment to DEI by aligning actions with stated values and ensuring that DEI principles are integrated into every aspect of the organisation.

Implementing human-centric practices, worker education, and DEI initiatives is critical for overcoming manufacturing companies' social challenges. These approaches can enhance manufacturing productivity, promote adaptability and innovation, and improve employee engagement and wellbeing.



Technological actions

The booming development of advanced technologies drives the global manufacturing sector to react and adapt swiftly.

Drivers

On the one hand, the manufacturing sector is expected to act locally but, on the other, to perform in a highly variable global landscape. In the last five years, there have been disruptions to the supply chains with COVID-19, trade wars, military operations, and new environmental regulations aimed at reducing carbon emissions, which have significantly impacted supply chains. Additionally, limited access to resources and raw materials, soaring energy prices and regulations for reduced energy usage have put the industry under more pressure. As a result, manufacturers are forced to innovate to produce more qualitative and greener products with fewer resources and less dependence on raw materials. This has led manufacturers to push for flexibility and modular production while aiming to make more products with fewer personnel and using fewer resources. Because of this, manufacturers are now pushing for modular production and flexibility to produce more goods with fewer workers and resources. The old economies of scale are ineffective under this new regime, and to satisfy the wide range of market demands, a shift towards economies of scope is needed. One of the main forces behind the industry's investigation and implementation of new technologies is the need for efficiency and flexibility.

Another driver is the race for early adoption of emerging technologies to obtain a competitive advantage. Early adopters of Industry 4.0 technologies such as CPS, Industrial Metaverse and digital twins, Artificial intelligence (AI), Gen AI, and AR/VR will present better quality, higher customer satisfaction, faster ramp-up times and time-to-volume, gaining market leadership in their respective industries. Higher ESG ratings lead to better investments, and becoming a pioneer of Industry 4.0 contributes to the company's branding and is considered a leader in sustainability and forward thinking. However, inherent risks are also connected to the race, such as technological obsolescence due to rapid technology cycles, mismatches between investments and market demands, and slow skill growth with constant workforce training.

Since 2022, there has been a booming development of Gen AI, which presents significant opportunities for innovations in manufacturing as well. The previous applications of the complex generative design can be even further improved with LLMs by using natural language and becoming human-centric. Optimisation and explicability of production and planning and scheduling orders are expected to be the next step after vertical integration of all layers, shop floor, enterprise, and facility. Generative AI will, therefore, support the economies of scope and facilitate mass customisation. Its integration into IT systems will enhance predictions of customer expectations and desires, while its application on the shop floor will enable predictive maintenance and predictive operation capabilities. GenAI radically changes how manufacturers approach innovation and problem-solving by simulating outcomes, generating models, and offering sophisticated decision-making tools. The difficulty, though, is appropriately integrating GenAI into current interoperable and secure systems.

Pressures

To remain competitive in such a variable and fast-moving landscape, manufacturing has to be up to date, with high-quality, green(er) products and sustainable practices. The rapid pace and advancement of technologies, such as AI, IIoT, and automation, put pressure on the manufacturers that if they do not act, they will fall behind, which is fundamental to a certain degree. Still, without a roadmap and a plan, reacting alone to the feeling of keeping up is riskier than investing time to assess readiness levels. The sense of losing ground and market share is intensified when competitors are quicker to adopt such innovations, which often leads to significant investments in the latest technology. Rushing into new technologies with clear long-term plans, a defined roadmap, and clear prioritisation areas usually results in costly mistakes, and some systems can quickly become obsolete or disjointed if the integration is performed uniformly across the organisation.

Manufacturing must become agile and flexible and quickly adapt to varying customer needs. It's expected to be simultaneously sustainable, resilient, and affordable. The investments to adopt technologies before their highest maturity levels, for instance, being an early adopter, have limited the years to see the result. The scale that the technologies require to be adopted puts pressure on the decision-makers to present a reduction of costs, tangible evidence of savings, and higher market shares while reducing the time needed for their return on investment (ROI). In many cases, the expectations of adopting new technologies are relatively high, which often results in terminating or neglecting innovation projects and pilots before their value is estimated correctly. To develop fast results and instantly reap the benefits of innovations, manufacturing companies must consider more aspects of their enterprises and not focus solely on technology. For example, the personnel's skill level, the learning and development structures, the company's understanding of new technologies, its culture and strategy, and the

collaboration levels among its departments must be modernised and aligned to achieve revenue maximisation.
With the rise of Gen AI, misinformation is spreading and becoming an increasing concern in manufacturing. Although GenAI provides solid data analysis, design, and production optimisation capabilities, it may produce false or misleading results if it is not taught or used correctly. Erroneous AI-generated predictive models, for example, can overstate specific trends or present inaccurate data, forcing firms to make expensive decisions based on incorrect information if they trust its results entirely.
As the volume of AI-generated content and data increases, the risk of misinformation is even higher. Decision-makers are facing the challenge of distinguishing valuable insights from noise and validated from invalidated data. More reliance on such systems will add further pressure on companies to establish more accurate and more efficient verification processes, requiring the respective expertise and experience of the personnel involved. Therefore, manufacturers should invest in training and educational programmes, purchase validated systems with responsible data and AI, and educate their teams to critically evaluate AI-generated information to avoid errors and inefficiencies.

State

The ecosystem's boundaries will change due to the potentially rising competition, changing lifecycles of solution development, and the increasing risk of misinformation. Applying advanced technologies can bring new stakeholders into the ecosystem and reshape the existing ecosystem. Some stakeholders in the current ecosystem could also be unnecessary in the future and, therefore, excluded from the newly established ecosystem. Newly developed technologies can foster new solutions that may substitute existing ones. Applying more advanced technologies, such as AI, IIoT, and digital twins, will trigger the shift of human roles, necessitating upskilling and the reskilling of existing personnel.

With technological advancement, we are observing that new markets are emerging, and the use of technology demands that the synchronisation of the markets and networking change accordingly. The type of innovation is crucial to the extent to which networking will change. For incremental innovation, the changes are not as significant as for radical innovation. However, there is this stagnant dilemma that all innovation is becoming incremental at the larger scale; nevertheless, systematic changes made at the firm level could still be radical for that particular firm.
The potentially rising competition, changing lifecycles of solution development, and the increasing risk of misinformation can also make the sustainable ecosystem imbalanced. The anticipated colossal power consumption will challenge the current energy generation and supply. The growing demand for semiconductors and batteries can damage the mining of critical components that compromise sustainability's social and environmental perspectives to chase more profit. There are many driving forces that can disrupt the balance of the ecosystem. The rise in GHG emissions and governance issues of the different economies causes imbalances in the ecosystem. Thus, to balance the ecosystems, policy changes are being made on the global level to ensure the reduction in carbon footprint and reusable energies. The European Green Deal and the European Commission's energy initiatives will cause significant changes in promoting cleantech resources to be used in ecosystems.

Impacts

The booming industrial applications of various technologies bring significant benefits and opportunities to the manufacturing sector. Applying deep technologies, like AI, IIoT, and digital twins, will promote manufacturing productivity, efficiency, and sustainability. Nevertheless, the manufacturing sector will have increasing concerns about the trustworthiness of advanced technologies. As the manufacturing sector applies profound learning-based AI algorithms in diverse scenarios, such as product design, production optimisation, and maintenance prediction, the so-called "black box" issue around existing deep learning models confuses practitioners and prevents them from fully convincing their internal decision-makers and customers. Similar problems arise when other digital technologies are applied.

As one of the three pillars of Industry 5.0, resilience is increasingly important when developing and applying technical solutions to the manufacturing sector. The consensus is that any technical innovation should be developed and used to strengthen the resilience of the overall or part of the production system in one way or another. For example, with AI-powered systems applied, the manufacturing sector can better optimise the production and maintenance schedules and predict the future occurrence of disturbances. VR can enable the manufacturing sector to have meetings online or upskill and reskill employees without prototypes or physical facilities. AI-powered digital twins can make better decisions regarding real-time production scenarios without human interference. Intelligent robots can work better for and with humans, enhancing production by creating a safer and more ergonomic working environment and improving efficiency and quality.
Although applying advanced technologies to the manufacturing sector has massive potential benefits, there are also some challenges. The enormous application of digital technologies will impose immense pressure on power and hardware. The gigantic computing servers supporting widely applied AI applications are anticipated to require considerable semiconductor investment and

consume enormous amounts of electricity. The ever-growing interconnected manufacturing system will pose significant challenges to guaranteeing cybersecurity.

The socio-technological shift towards sustainable, resilient, and human-centric development has driven the change in customers' mindsets and preferences in choosing the products they purchase. Customers increasingly consider the ethical perspective when selecting products.

These conscious customers invest in brands that demonstrate genuine ethical commitments instead of buying products. With more and more devices connected to the internet and the persistent advances in communication technologies, customers have become increasingly well-informed and better able to retrieve information from diverse pathways. Customers can retrieve more information about the overall value chains with more and more technologies. Therefore, the manufacturing sector should be more committed and transparent in integrating integrity into their business. This integration is not only beneficial but essential as well. Integrating integrity will strengthen the organisation's reputation and customer loyalty, fostering a more robust business to achieve tremendous success. On the contrary, failure to do so can undermine customer trust and brand reputation, further damaging the overall business or even leading to its eventual elimination.

Responses

Whenever a firm proposes a vision or strategy change, the managers must make many changes to become technology ready. The firm's strategy must be adjusted to accommodate the absorption and adaptation challenges.

Furthermore, organisations need to consider their technology strategy more cautiously than ever. Competition between competitors, the fear of being obsolete, and the emergence of new business models can revolutionise the industry radically. The industry must consider changing its attitude towards technological innovations and its philosophy of integrating innovative technologies into its business.

Companies should also consider the changes in their business models to react to the changing ecosystem. The business model also has significant design changes because of the technology shift. The previous WMF Report (2023) went into detail on business model changes (servitised business models) and how each component of the business model changes when enabled through technology such as artificial intelligence (AI). This causes manufacturers to change their supply chain and value networks dynamically. The company's managers bring about one significant response to technological changes. Technological changes in businesses require research, development, and deployment mechanisms to deal with the challenges that may arise and prepare the technology. The European Union recommends nine levels of technology readiness level (TRL), as shown in Figure 35.

For this, companies need to validate their strategy by ensuring they have the right resources, knowledge, and culture to foster technology adoption in their company.

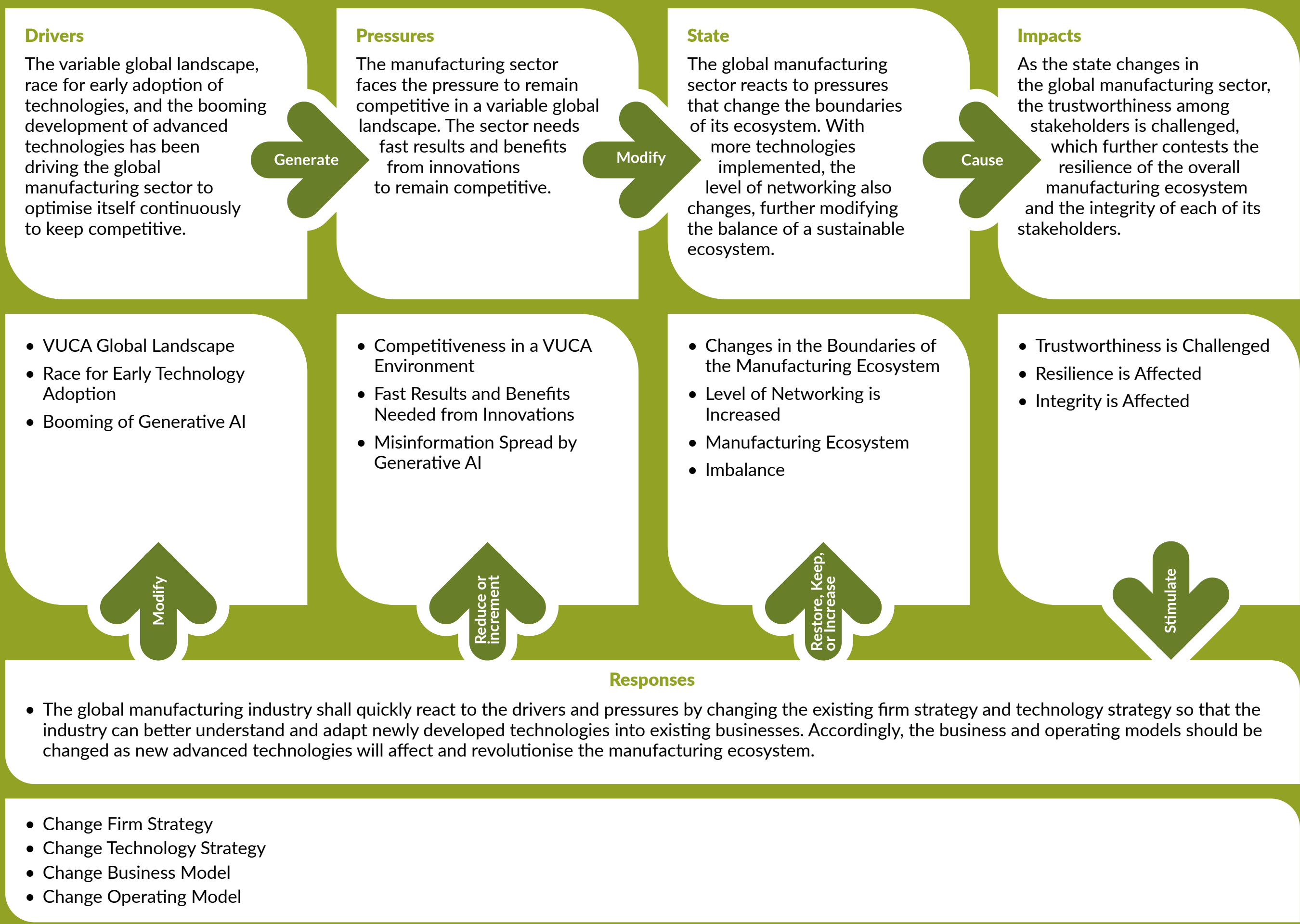
The manufacturing sector will adaptively reform its strategy for reacting to technology and integrating it into existing production by responding to accelerating technology development. The overall consideration of the technological transition will enable the manufacturing sector to achieve sustainability, resilience, and human-centricity in the near future.

Technology Readiness Level (TRL)

Figure 35

TRL scale diagram

(Source: EU H2020)



Legal actions

Without timely legal adaptations, the manufacturing sector could find gaps in safety, privacy, and social equity that could hinder the broader societal progress envisioned by this revolution.

Drivers

Several factors drive the legal aspects of the manufacturing sector. In light of new global priorities, which have reinforced the need to explore the role of humans in manufacturing alongside the pressing environmental situation and the need for more resilient systems, some identified drivers are given below.

One of the main drivers impacting legal actions in the manufacturing sector is the rapid development of digital technologies that are part of the digital transformation of manufacturing companies. For instance, AI, a technology that has quickly revolutionised companies' activities, has brought along many questions as companies see it as a significant opportunity to enhance efficiency, precision, and innovation, driving engagement from a legal perspective. Moreover, trust in AI-human interaction, especially in decision-making, varies among individuals, making designing fair, transparent, and secure systems crucial. This topic can also benefit from robust legal frameworks; companies can build sustainable human-AI collaborations that support a more inclusive and trustworthy integration of AI in the workplace.

Another driver for legal actions in the manufacturing sector is the need for a skilled workforce. In this sense, legal frameworks must evolve to address the potential marginalisation of specific jobs and skills, ensuring that workers' rights are protected in an increasingly AI-driven world. This includes updating workplace safety and risk management norms to account for integrating enabling technologies and AI, thereby safeguarding worker protection and reducing employer liability. Legal frameworks could evolve to mandate the integration of AI or enabling technologies in high-risk industries, thereby enhancing worker protection and reducing liability for employers.

One more driver for legal action includes the urgent need for harmonious and sustainable innovation. As the global legislative landscape evolves to address the urgent need to mitigate climate change, manufacturing companies are driven to proactively adapt their strategies to anticipate, rapidly respond and comply with drastically enhanced carbon regulations.

Pressures

The manufacturing sector faces pressures that guide it towards accelerating the creation of legal frameworks, regulations, and standards as part of its approach to bullet-proofing and problem-solving in the current industrial context.

Central pressure includes the perceived threats to human and societal values with the existing gap between technological and human cooperation. Despite being a work in progress, designing technologies with human values at their core necessitates rapidly developing a comprehensive legal approach. This includes incorporating ethical principles, privacy protection, inclusivity, societal impact, and accountability into developing and deploying technologies. As human-AI teaming becomes more prevalent, ambiguity in liability and responsibility must be addressed to prevent legal disputes over errors or failures. Legal ambiguity may arise over who is responsible – the human operator, the AI system, or the developer – leading to potential conflicts and legal disputes.

Another pressure faced in the manufacturing sector is the inefficient use of resources, generating waste and emissions. In this sense, the pressure to reduce carbon footprints drives companies to integrate comprehensive carbon management practices into their operational and innovation frameworks. Moreover, with the introduction of stringent biodiversity and ecosystem restoration regulations, manufacturing companies need to respond strategically and operationally to meet legal requirements while managing risks.

This area also adds pressure to collaborate, as manufacturers must focus on internal changes and engage in industry-wide collaborations and policy advocacy. By participating in forums that shape carbon regulation policies, firms can influence the development of feasible and practical regulatory frameworks. Collaborations, such as those through industry consortia or partnerships with environmental organisations, enable shared solutions for carbon reduction, such as joint investments in renewable projects or shared carbon capture facilities.

From a regulatory perspective, not managing biodiversity strategically will become a significant risk for manufacturing companies in the future. Manufacturers should integrate biodiversity risk management into their corporate strategies. Through comprehensive biodiversity impact assessments, firms can anticipate potential regulatory impacts and adapt their practices accordingly.

The rapid technological development of connectivity and data use puts pressure on the manufacturing sector, increasing the risk of cyberthreats and other data-related concerns. This pressure stems from the fact that long-established companies in the manufacturing sector embrace digitalisation to the extent that, in some instances, they also open themselves up to a new breed of vulnerabilities. In this sense, the need for regulatory frameworks, regulations, and standards becomes ever more relevant to regulating how cyber protection can support the protection of individual companies and complete value chains. In this sense, data becomes an element of concern with inquiries such as "Who owns it?", "Who manages it?", and "Who is responsible for it?". Some of these pressures can lead to actions such as continuously screening and monitoring suppliers to evaluate their cybersecurity readiness, investing in encrypting communications and developing robust incident response plans which support the resilience of the whole manufacturing sector.

State

The regulatory landscape for human-centric manufacturing is still in its developmental phase. Although there is increasing recognition of the need for a human-centred approach within the industry, clear and comprehensive guidelines still need to be developed. This lack of mature legal frameworks creates uncertainty for companies looking to integrate human-centric elements, such as employee wellbeing initiatives, ergonomic designs, and advanced technologies like virtual reality training, which need to be more recognised in many regions due to legal and cultural differences. As a result, manufacturers often need help implementing these practices effectively, especially in diverse legal environments.

Similarly, sustainability regulations within the manufacturing sector must be revised due to the slow operationalisation of existing frameworks. While many legal instruments and standards promoting environmental and social sustainability exist, their practical implementation is inconsistent. Companies often face gaps in compliance, as regulations require interpretation, and enforcement is weak or delayed. This hampers the industry's ability to meet sustainability goals and align with environmental responsibilities, leading to uneven progress across different regions and industries. Manufacturers are often left without clear guidelines on integrating sustainable practices, further complicating the push towards a more responsible manufacturing sector.

In parallel, the rise of AI and digital technologies in manufacturing has prompted the emergence of new regulations, but these frameworks are still evolving. As AI and automation become integral to modern manufacturing processes, new legal concerns surrounding data privacy, ethical AI use, and the transparency of AI decision-making are gaining attention. Although these regulations aim to address the transformative impact of AI on labour dynamics and operational accountability, they are still in the early stages of development, as mentioned in Chapter Two, with new treaties being signed such as the AI Convention.[200] Therefore, much work remains to ensure that AI integration into manufacturing boosts efficiency and adheres to ethical and legal standards.

Impacts

Changes in legal frameworks and regulations within the manufacturing sector can potentially drive transformative impacts and affect human and societal wellbeing, eco-efficiency best practices, and human-technology symbiosis:

- *Improved human and societal wellbeing* – Changes in regulatory frameworks prioritising human-centricity, safety, and inclusivity in manufacturing can enhance wellbeing for workers and society. These regulations ensure healthier work environments and reduce workplace risks by focusing on ergonomic safety, mental health, and fair labour practices. They also foster job satisfaction and empowerment by valuing workers as active contributors rather than mere operators. Additionally, regulations that emphasise social inclusion can help marginalised groups access better employment opportunities, promoting social equity and cohesion in the workforce.
- *Increased clarity on eco-efficiency best practices* – New legal frameworks that provide more explicit guidelines on eco-efficiency can significantly improve environmental sustainability in manufacturing. By offering specific standards for reducing energy consumption, managing waste, and optimising resource use, these regulations help companies adopt best practices more efficiently. This clarity drives cost savings and operational efficiency and encourages businesses to embrace circular economy principles. In the long term, such regulations can foster innovation in sustainable technologies and strengthen a company's commitment to corporate environmental responsibility.
- *Maximise the value of human-technology symbiosis in manufacturing* – Legal frameworks supporting human-technology symbiosis will shape how humans and AI work together in manufacturing. The increasing reliance on AI and automation in manufacturing shifts the nature of work from purely manual or routine tasks to a focus on creative problem-solving and innovation. Legal frameworks must evolve to accommodate this transition, ensuring that AI systems augment rather than replace human workers. Regulations can promote training programmes that equip workers with the skills to collaborate with AI systems, transforming them into partners rather than mere operators. As AI becomes a co-worker in creative tasks and decision-making processes, legal frameworks must define clear lines of responsibility and accountability. This includes addressing questions about liability when AI systems make decisions or when errors occur in collaborative tasks. Without legal clarity, there could be confusion over whether humans, machines, or companies that design AI systems are liable for mistakes or failures in production.

Responses

Futureproofing means crafting laws that evolve with the industry, allowing manufacturers to thrive in continuous change while maintaining ethical standards and promoting long-term sustainability. To do so, the following vital responses are recommended to reduce pressures and mitigate the potential negative impacts (stifling innovation, unregulated technologies, lack of actionable green strategies):

Tackle the risk of overregulation that could bring inertia to innovation practices

In an era of rapid technological advancements in manufacturing, legal frameworks must remain flexible enough to support innovation rather than hinder it. Overregulation, where legal restrictions become too stringent or prescriptive, could stifle creative problem-solving and prevent companies from experimenting with new technologies. The regulatory environment should be adaptive, allowing manufacturers to innovate with emerging technologies like AI, VR, and automation, while maintaining necessary oversight. This could be achieved by adopting more dynamic regulatory approaches, such as regulatory sandboxes. These controlled environments allow companies to test technologies without the entire burden of regulatory compliance, encouraging innovation while providing regulators with real-world data to refine policies. In this way, manufacturers can push the boundaries of what's possible without being constrained by outdated or overly rigid legal structures.

The voices of companies need to be considered by regulatory institutions to avoid jeopardising industrial success

Regulatory institutions must actively engage with industry leaders to create legal frameworks that are both effective and conducive to industrial success. A top-down regulatory approach, where laws are imposed without consultation, risks disconnecting legal requirements from the realities of the manufacturing floor (see how rules have recently put pressure on the automotive or steel-making industries.[201]) Companies' perspectives, challenges, and operational needs must be integrated into policymaking. Regular dialogue between businesses and regulators can ensure that laws balance protecting societal interests, such as workers' rights and environmental sustainability while fostering industrial growth.

For instance, initiatives connected to ESG issues, reporting processes, and compliance obligations should involve input from all levels of the organisation into the regulatory agencies. This way, it can support cultivating a knowledgeable workforce engaged in sustainability practices and help firms enhance their capacity to meet compliance demands consistently and accurately. Additionally, leadership development programmes in sustainability need to be prioritised to ensure that the needs of the companies are correctly captured and that top management can lead by example and foster a culture of environmental responsibility and ethical governance.

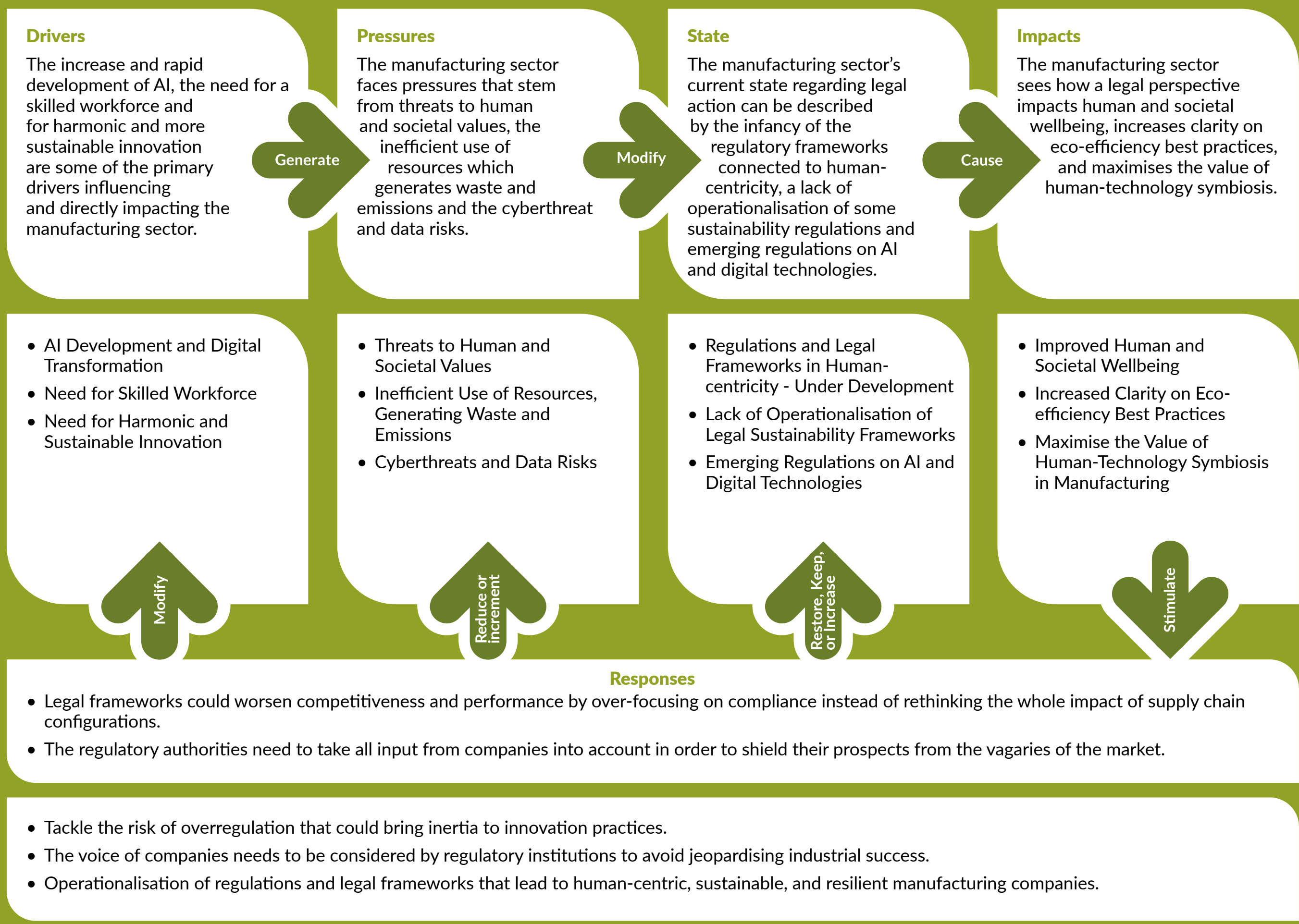
A participatory, inclusive regulatory process allows manufacturers to innovate confidently without fearing unpredictable or restrictive legal changes that could jeopardise their competitiveness.

Operationalisation of regulations and legal frameworks that lead to human-centric, sustainable and resilient manufacturing companies

The key to futureproofing the manufacturing sector is effectively translating legal frameworks into operational realities. It is not enough to have laws in place; these regulations must be actionable and integrated seamlessly into day-to-day operations. Operationalising these regulations might involve setting measurable standards, such as carbon emissions limits or workplace safety benchmarks, and providing companies with the tools and resources to comply effectively. Operationalising these regulations should account for the varying capacities of different-sized companies. For large companies, regulations can include strict measurable standards, like carbon emissions limits or workforce safety requirements, since these organisations typically have more resources to meet such benchmarks. Companies should deploy advanced technologies to reduce energy consumption and decrease carbon emissions in terms of operationalising efforts towards addressing carbon regulations and enhancing energy efficiency across operations. Some initiatives include upgrading to energy-efficient machinery, optimising production cycles to minimise energy waste, and retrofitting facilities with state-of-the-art insulation and lighting systems. Moreover, leveraging smart manufacturing technologies is another strategic response addressing direct and indirect carbon emissions.[202] Integrating Internet of Things (IoT) devices, automation, and artificial intelligence into manufacturing processes allows for real-time monitoring and precise control of energy use. Also, transitioning to renewable energy sources is a critical response for manufacturers facing stringent carbon regulations. [203] Companies can drastically reduce their reliance on fossil-fuel power by investing in solar, wind, and other installations on-site or through renewable energy certificates (RECs).

Large corporations can be mandated to invest in innovation and human-centric practices while supporting smaller companies through partnerships or shared platforms. On the other hand, the legal framework needs to be more flexible and supportive of SMEs and microenterprises, recognising the resource constraints smaller companies face. Legal frameworks should include incentives like subsidies, tax relief, or simplified compliance processes to ensure these businesses can afford to implement human-centric and sustainable technologies.

The legal frameworks established today will not only shape the future of manufacturing but will determine how human values, environmental priorities, and technological progress can be integrated. By developing inclusive and forward-looking regulations, we can move towards a future where industry thrives, workers are protected, and sustainability becomes a priority.



Environmental actions

Industry 5.0's human-centric approach emphasises sustainability through circular economy practices and Regenerative Manufacturing Systems. It aims to reduce waste, use renewable resources, and maximise societal value while minimising environmental impact.

Drivers

The global manufacturing sector is driven by several key factors that shape its development and evolution. Economic growth is a primary driver, fuelling the demand for manufactured goods and leading to increased production and resource consumption. As economies expand, manufacturing industries are pushed to scale up operations, adopt new technologies, and explore new markets to meet rising consumer demand. The European Commission, in its industrial strategy, highlights the role of economic growth in driving the competitiveness of the manufacturing sector, emphasising the need for innovation and efficiency to sustain growth.[204] Technological innovation is another crucial driver that propels the manufacturing sector forward. Advances in automation, digitalisation, and artificial intelligence are transforming manufacturing processes, making them more efficient, flexible, and sustainable. The European Commission's focus on Industry 5.0 reflects the importance of integrating human-centric technologies that enhance productivity and contribute to social and environmental goals.[205] These innovations are essential for maintaining the sector's competitiveness in a rapidly evolving global market. Consumer demand for sustainability is increasingly influencing manufacturing practices. As awareness of environmental issues grows, consumers demand eco-friendly, ethically produced, and resource-efficient products. This shift in consumer behaviour drives manufacturers to adopt sustainable practices, reduce their environmental footprint, and engage in circular economy initiatives. The European Green Deal underscores the importance of aligning manufacturing activities with sustainability goals to meet consumer expectations and regulatory requirements.[206]

Pressures

The drivers of the global manufacturing sector generate significant pressures that influence how the sector operates and evolves. One of the most pressing challenges is resource depletion. As manufacturing activities increase to meet economic and consumer demands, the extraction of raw materials intensifies, leading to the depletion of finite resources. This pressure is particularly acute for critical raw materials essential for advanced technologies, as highlighted in the European Commission's Raw Materials Initiative.[207] The scarcity of these materials threatens the sustainability of manufacturing processes and raises concerns about the long-term availability of essential resources. Environmental regulations and climate changes impose another layer of pressure on the manufacturing sector. Governments and international bodies increasingly enact stringent rules to reduce emissions, manage waste, and conserve resources. These regulations compel manufacturers to adopt cleaner technologies, improve waste management practices, and reduce their environmental impact. The European Union's regulatory framework, including the Circular Economy Action Plan, sets ambitious targets for reducing waste and promoting resource efficiency, creating challenges and opportunities for manufacturers. Energy demands continue to exert pressure on the manufacturing sector, particularly as the need for energy-intensive processes persists. The shift towards renewable energy sources and reducing carbon emissions require manufacturers to invest in energy-efficient technologies and sustainable energy solutions. The European Commission's Climate and Energy Framework emphasises the importance of energy efficiency and the transition to renewable energy in achieving the EU's climate goals.

State

The current state of the global manufacturing ecosystem reflects the cumulative impact of various drivers and pressures. One of the most prominent characteristics is a lack of resources. As the demand for raw materials continues to rise, the availability of essential resources is becoming increasingly limited. This scarcity affects the cost and availability of materials and poses a significant challenge to the sustainability of manufacturing processes. The European Commission's Circular Economy Action Plan emphasises addressing resource scarcity through improved resource efficiency and adopting circular economy practices.

Biodiversity is another critical aspect of the current state of the manufacturing ecosystem. The intensive use of natural resources, combined with the generation of waste and emissions, has led to significant environmental impacts, including pollution, habitat destruction, and biodiversity loss. The European Green Deal highlights the urgency of addressing these environmental challenges to ensure the long-term sustainability of the manufacturing sector and the broader economy. On a more positive note, ongoing efforts to improve energy efficiency are a notable feature of the current state of the manufacturing ecosystem. Manufacturers increasingly adopt energy-efficient technologies and processes to reduce their energy consumption and carbon footprint. These efforts are supported by the European Commission's initiatives to promote energy efficiency as a critical component of the EU's climate and energy policies.

Impacts

The global manufacturing ecosystem's pressures and state significantly impact the sector and beyond. One of the most immediate impacts is the increase in operational costs. As resources become scarcer and environmental regulations more stringent, manufacturers face rising costs related to resource procurement, waste management, and compliance with environmental standards. These cost pressures can affect profitability and competitiveness, particularly for manufacturers not fully integrating sustainable practices into their operations.[208] The shift to green technologies has another significant impact on the manufacturing sector. Manufacturers are increasingly adopting green technologies and processes in response to environmental pressures and consumer demand for sustainability. This shift reduces the ecological impact of manufacturing activities and positions companies to meet future regulatory requirements and consumer expectations. The European Commission's focus on green innovation as part of its industrial strategy highlights the importance of this transition for the sector's future competitiveness. Regulatory compliance challenges also have a significant impact on the manufacturing sector. Navigating the complex and evolving landscape of environmental regulations requires manufacturers to invest in compliance systems, develop new processes, and adapt to changing standards. These challenges can be particularly burdensome for small and medium-sized enterprises, which may lack the resources to manage compliance effectively.

Responses

Companies are adopting various strategies to promote sustainability and resilience in response to the drivers, pressures, and impacts shaping the global manufacturing sector. One of the most effective responses is the adoption of circular economy practices. By reducing waste, reusing materials, and optimising resource efficiency, manufacturers can mitigate the pressures of resource depletion and environmental degradation. The European Commission's Circular Economy Action Plan provides a comprehensive framework for integrating circular economy principles into manufacturing processes, highlighting the potential for environmental and economic benefits. The implementation of regenerative manufacturing systems is another critical response. These systems aim to restore ecosystems and minimise environmental impacts by incorporating principles of regeneration and sustainability into manufacturing processes.

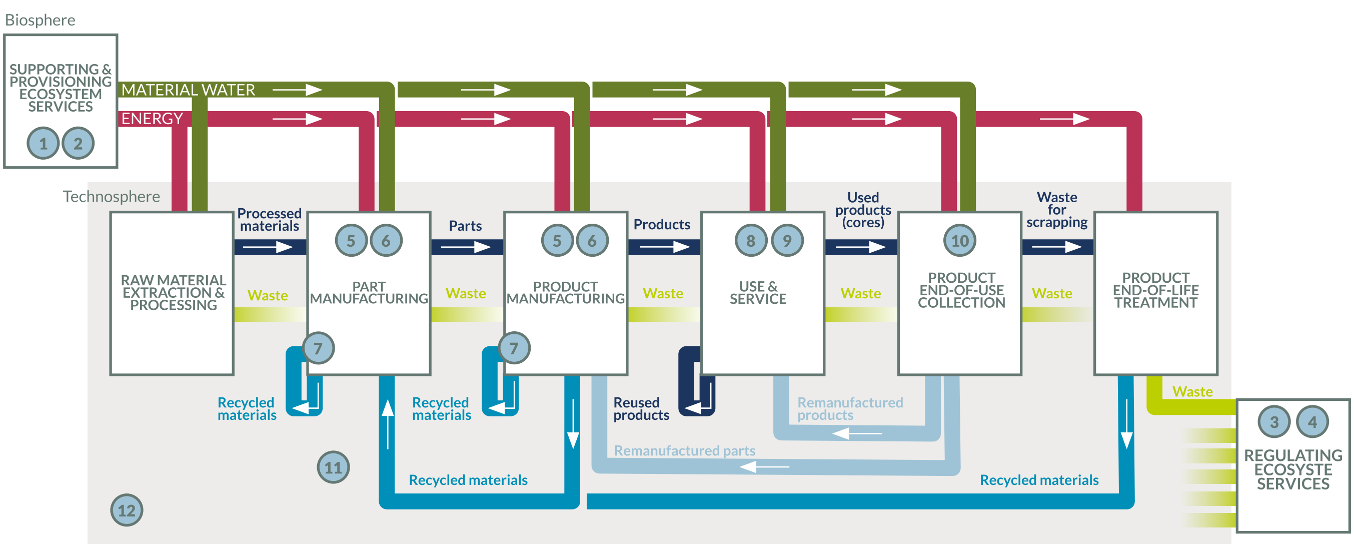
As the European Green Deal outlines, this approach aligns with the European Union's vision for a sustainable and resilient industrial future. By adopting regenerative practices, manufacturers can contribute to restoring natural systems while enhancing their sustainability. Innovation in green technologies is also a critical response to the manufacturing sector's challenges. Developing and deploying new technologies that reduce environmental impacts, such as renewable energy systems, energy-efficient processes, and sustainable materials, is essential for achieving long-term sustainability goals. The European Commission's focus on green innovation as part of its industrial strategy emphasises the importance of technological advancement in driving the sector's transition towards sustainability.

The new manufacturing concepts driven by Industry 5.0 emphasise human-centricity, sustainability, and resilience, with sustainability and resilience closely tied to environmental actions. Sustainable manufacturing integrates processes that produce high-quality products using fewer and more sustainable resources, ensuring safety and reducing environmental impacts throughout the product lifecycle.[209] To achieve this, companies must focus on the circular economy, a system that keeps materials in continuous use and regenerates nature. By adopting circular economy practices, businesses can reduce costs, contribute positively to society, and increase revenues. Achieving these goals requires the adoption of Regenerative Manufacturing Systems.[210] These systems emphasise using renewable, non-toxic, and locally abundant resources, ensuring that processes and products are safe and sustainable. Resource consumption must align with natural regeneration rates, and waste should be minimised or eliminated. When waste is unavoidable, it should be treated to minimise environmental impact. Processes and systems should generate net environmental benefits, restoring natural resources and reversing harmful effects. Additionally, these systems should maximise resource efficiency, prolong product life through durability and reparability, and enable material collection, reuse, and recycling. Ultimately, the goal is to maximise societal value per unit of resource consumed, aligning manufacturing practices with the principles of sustainability and circularity.[211] The framework for applying the main principles in the Regenerative Manufacturing Systems is presented in Figure 36.

Figure 36

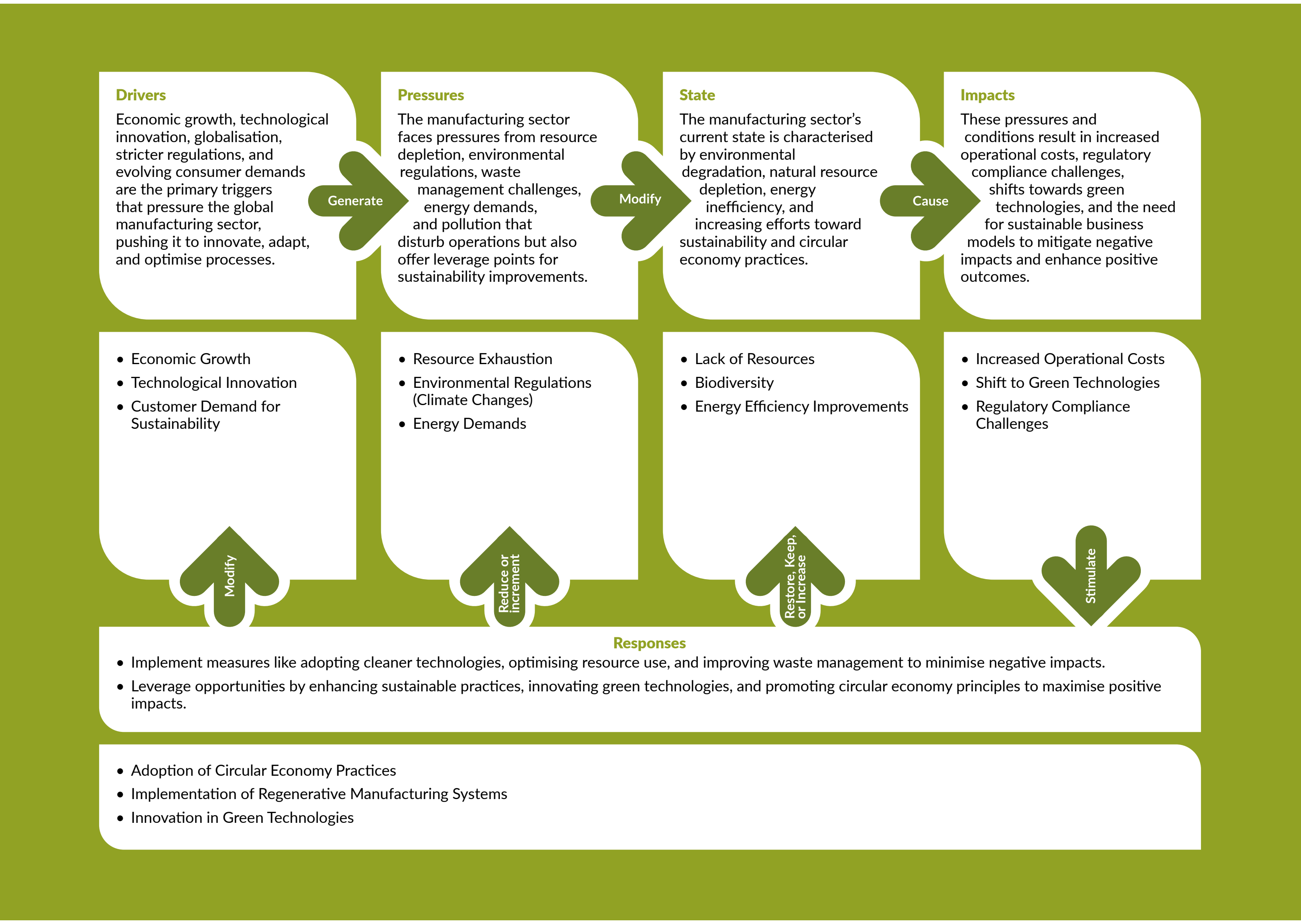
Regenerative Manufacturing Systems

(Source: Despeisse, 2023)



Companies should embrace a spectrum of strategies outlined in the restore-preserve-enhance framework to implement Regenerative Manufacturing Systems effectively. Restore strategies focus on repairing ecosystems after industrial activities, acknowledging the need to mitigate negative impacts. These strategies typically involve minimal changes to business models, aiming to restore ecosystems to their pre-disturbance state.[212] Preserve strategies are more proactive, striving to maintain the existing state of ecosystems by ensuring that business activities respect ecological boundaries. This approach often requires adapting business operations to avoid surpassing the ecosystem's carrying capacity, thereby preserving its functionality over the long term. Enhance strategies go beyond preservation, actively seeking to improve ecosystem health and resilience. These strategies involve innovative, participative approaches that ensure the sustainability of ecosystems and enhance their ability to support life.[213] By adopting these strategies, companies can transition from merely minimising harm to generating positive environmental impacts, aligning their operations with broader sustainability goals, and contributing to the long-term viability of the business and the ecosystems they depend on. Companies must incorporate two critical approaches, the Systems-Based Concept and Adaptive Management, to implement Regenerative Manufacturing Systems effectively. The first principle asserts that business sustainability should aim for the sustainability of the entire social-ecological system rather than focusing solely on individual business success. The second principle emphasises the need for an adaptive management approach, which aligns with social-ecological systems' complexity and dynamic nature. This adaptability ensures that businesses can respond effectively to the evolving challenges within these systems.

Technological innovation and changes in consumer behaviours are crucial drivers boosting the creation of more environmentally friendly regenerative manufacturing systems, positioning companies to meet future regulatory requirements and consumer expectations.



4

Key Recommendations

The World Manufacturing Foundation, in collaboration with global experts, is pleased to present the Ten Key Recommendations of the 2024 World Manufacturing Report. We hope that our readers can take inspiration from these recommendations and work together to futureproof manufacturing companies and their supply chains in the face of a foreseen volatile, uncertain, complex, and ambiguous business environment in the forthcoming years.

1. EMBRACE CHANGE TO OVERCOME CRITICAL MANUFACTURING CHALLENGES IN A VUCA WORLD

- **Skills: Develop agility, adaptability, and resiliency skills in the leadership team and workforce to respond quickly and effectively to shifting circumstances, including unexpected situations.**
- **Technology: Embrace business intelligence & data analytics technologies that can assist in minimising uncertainty, boosting adaptability, and improving resiliency.**
- **Culture: Create a VUCA leadership and workforce culture capable of thriving amidst constant change and uncertainty.**

Today's global business environment can be classified as volatile, uncertain, complex, and ambiguous (VUCA). This environment impacts all facets of life and business, from consumption patterns to supply chain and manufacturing operations.

In this fast-evolving manufacturing world, resisting change is like swimming against the tide and can be considered futile. A manufacturing company may exhaust all its energy and resources while still being at the mercy of the global paradigm and having difficulty predicting geopolitical, social, and environmental events. In this setting, players who change their perception seem far better at adaptability and using scarce resources than those who do not embrace and resist change as an opportunity. Thus, tackling the emerging grand manufacturing challenges head-on with an open mind is fundamental for achieving continuous growth in a global competitive landscape that calls for rethinking business and operating models and strategies, adopting new advanced technologies, and exploring new markets and consumer needs. To adapt successfully to this VUCA environment, a positive mindset and a new or renewed skill set are essential. Leadership and the workforce must develop agility, adaptability, and resiliency skills, which often mean different things in different manufacturing industries, locations, and roles. Unfortunately, no cookie-cutter approach can be adopted as 'one size fits all'. Critically reflecting on the unique circumstances and starting points is a crucial first step in adopting the positive approach to embracing and leveraging change to overcome challenges.

Technological progress can offer vital means to help in the transition to and sustainment of embracing change. However, technology is not a silver bullet, and if rushed or adopted without the proper strategic vision, it can be counterproductive. For instance, if decisions on production capacity are based on flawed data, this can lead to a false sense of control and security and cause leaders to let their guard down, leading to disastrous results. In such a scenario, it is often better not to have advanced forecasting, allowing for a swift response and resolution of upcoming challenges. However, technology adapted in the right way can be an essential component in successfully navigating this VUCA world. In particular, adopting business intelligence and data analytics technologies has the potential to minimise uncertainty, boost adaptability and complexity management, and improve resilience. When adopting these technologies, the devil is in the detail; in this case, that often means data quality. As these data-based and analytical technologies derive insights from available data, focusing on acquiring and managing high-quality data from trustworthy sources is a fundamental requirement for their adoption and usage. Given that (smart) manufacturing today involves complex relationships in supply networks, relevant data resides with different organisations, business units, and market regions. Facilitating data and information exchange requires trust and coordination among supply chain partners, encompassing technical and non-technical data integration and information systems interoperability challenges.

The previous point already hints at the need to rethink relationships and corporate culture. To embrace change in a VUCA world, manufacturing companies may need to re-evaluate their approach to competitiveness. While this does not necessarily mean abandoning the competitive mindset, it may mean rethinking whether collaborating with a perceived competitor benefits both (coopeting) instead of categorically denying such requests. It is a brave new world, and whoever can stay agile and nimble is more likely to navigate it successfully in the long run.

2. LEVERAGE BUSINESS INTELLIGENCE AND DATA ANALYTICS TO NAVIGATE THE GRAND MANUFACTURING CHALLENGES AND OPPORTUNITIES

- **Skills: Become a data detective, with analytical and data storytelling skills, uncovering hidden trends, translating them into business insights, and driving action-taking.**
- **Technology: Make use of business intelligence & data analytics technologies to analyse (big) data and present actionable information to decision-makers.**
- **Culture: Promote a business intelligence & data analytics culture that values data-driven decision-making.**

In today's manufacturing world, understanding the market trends, consumer preferences, and competitive forces driving change in the sector is a must. Business insights to anticipate shifts and disruptions and prepare accordingly are new sources of competitive advantage in a VUCA world. As a result, the novel adaptive enterprise model represents the edge of innovation and resilience for manufacturing companies, according to the new digital era.

The transition to the adaptive enterprise model, an operating model based on the availability of information and information processing technologies capable of supporting data-driven decisions, makes it necessary to introduce new skills related to the definition, implementation, and application of data-rich models consistent with the business objectives and with the possibility of glimpsing new trends within the available data and information. The necessary skills for its adoption can be classified into three macro dimensions. Of an organisational nature, the adaptive enterprise requires an open and highly collaborative organisational model capable of extending the concept of "the enterprise" outside the company's four walls and along its entire value chain, known as "the extended enterprise". The second dimension, linked to data science and the ability to incorporate strategic enterprise (computer) information systems for supporting critical business operations, is of a technological nature. In the adaptive enterprise, constructing a data-rich model capable of representing the company with its assets and business model within its ecosystem, leveraging available information processing technologies, is of fundamental importance. The third and last dimension concerns the managerial nature. In an adaptive enterprise, a managerial model devoted to dynamism and innovation is necessary but simultaneously capable of keeping the company anchored to its mission and founding values.

The implementation of the adaptive enterprise model is possible thanks to the correct adoption of the information processing technologies available today, which, in their joint use, allow the capture and conservation of large amounts of data and the extraction of the necessary business insights from it. From here, we move on to actionable information – the ability to use the insights in the strategy planning and execution phase of everyday business operations. As the basis of implementing the adaptive enterprise model, it is necessary to design a precise technological strategy and open a collaborative architectural model to achieve the maximum benefits of business intelligence for the company. A possible approach is based on the creation of a control tower. The control tower model is made up of two areas. Thanks to the collection of structured, semi-structured, and unstructured data and information, the first one makes it possible to describe specific conditions along the entire value chain and, with the adoption of big data analytics and artificial intelligence tools, intercepts any disruption while providing decision support to undertake measures to ensure business continuity. The second area of execution allows the recommendations provided by the first area of analysis to be implemented, taking advantage of the capabilities of the adopted information management systems.

In a global economic and industrial scenario polarised by big digital players, to ensure their success, manufacturing companies must be able to grasp the challenges and opportunities offered by new digital business and operating models based on the availability of large volumes of data and information and the enabling processing technologies to transform these into revenue. The technologies available today make it possible to implement the adaptive enterprise model, which, thanks to a data science approach, enables the creation of a company capable of adapting to changes in market conditions in line with its own business objectives and supply chain dynamics. To make this evolution possible, it is necessary to set up a new cultural model that favours the transition from silo organisational models towards open and collaborative ones so that it becomes possible to fully exploit the advantages of the adaptive enterprise model and its related data-driven business and operating model.

3. FOSTER INNOVATION AT THE HEART OF MANUFACTURING TRANSFORMATION

- **Skills: Develop skills for innovation such as creativity, adaptability, entrepreneurial thinking, and transdisciplinary work in the leadership team and workforce.**
- **Technology: Pursue technological innovation and organisational change to explore new business and operating models.**
- **Culture: Foster an innovation culture that embraces the opportunities found in incremental and radical transformations.**

The present global manufacturing competition arena is changing quickly, and manufacturing innovation is becoming not just a simple catchphrase but more a competitive necessity. At the centre of any outgoing industrial transformations, such as the digital and green transitions, is the capacity for innovation, which profoundly shapes the future of manufacturing industries' business and operating models and promotes their competitive edge. Consequently, if manufacturers want to remain competitive, they must embrace an ambidextrous innovation approach, with both incremental or exploitative and radical or explorative innovation approaches prioritised and balanced as part of their corporate strategy.

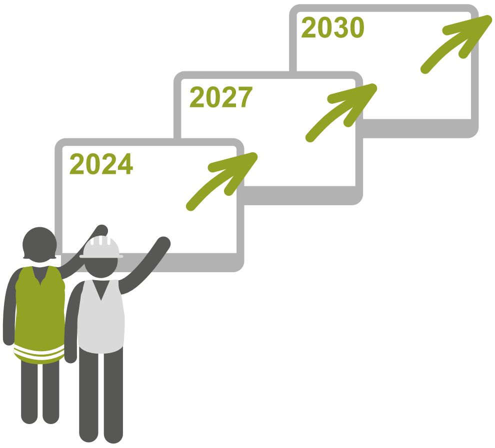
A manufacturing company that has consistently prioritised keeping its production operations as efficient as possible over the years may be able to sustain significant profitability. Still, this approach can also result in innovation stagnation, especially when confronted with fast-changing market dynamics and, in some cases, market disruptions. Thus, modern manufacturing companies need to develop a continuous and ambidextrous innovation mindset to break free from this cycle of stagnation. This required mind set entails investigating novel business and operating strategies and experimenting with new product designs and advanced manufacturing processes and technologies.

An innovative manufacturing company must be prepared to accept measured risks when exploring contemporary product designs and state-of-the-art manufacturing processes and technologies after years of playing safe. For example, an old manufacturing shop floor can be converted into an innovation sandbox to create a place where new manufacturing paradigms are tested or developed and novel product ideas are tried. Manufacturing innovation can flourish in this setting, creating the foundation for a competitive and innovative manufacturing company. To promote manufacturing innovation, a corporate culture that embraces fresh ideas and perspectives sees setbacks as teaching moments and defines success as the capacity for adaptation and change that must be established. Therefore, encouraging open communication, supporting employee-led initiatives, and recognising and rewarding creative solutions are ways to accomplish this needed cultural transformation. By doing so, manufacturing companies can embrace and foster an atmosphere where innovation is valued highly and engrained into the organisation's core values. Moreover innovation demands intentional action and dedication from all organisational levels. For creative, innovative ideas to grow, a culture of nurturing and vision setting are essential components of corporate and workforce leadership. It involves fostering a climate where groups can try new things, take calculated chances, and fail forward without worrying about the consequences.

To genuinely promote innovation, a company's success metrics must change in addition to its leadership. While traditional metrics such as quarterly profits still hold significance, they cannot serve as the exclusive indicators of advancement. Manufacturing businesses must consider new or renewed approaches to evaluate the success of their innovative projects. This could be done, for instance, by keeping tabs on how soon innovative concepts are introduced to the market, how they increase customer satisfaction levels, or even how they create new revenue sources. Manufacturers can then better understand the underlying worth of their innovation activities by expanding the definition of success.

Another essential component of practical manufacturing innovation is collaboration. Most progressive manufacturing companies actively seek collaborations and open innovation models, whether with academic institutions expanding their research, startups introducing them to novel, innovative ideas, or even rival companies in beneficial coopetive models. These mix of collaborations can infuse a manufacturing innovation pipeline with fresh ideas and views, fostering discoveries that might not have been achievable alone.

4. PLAN STRATEGICALLY DESPITE THE PACE OF DAY-TO-DAY MANUFACTURING BUSINESS OPERATIONS



- **Skills: Cultivate research, analytical, and critical-thinking skills in the leadership team to create innovative but viable business strategies and solutions.**
- **Technology: Use data and technology to improve not only strategic planning but strategy execution.**
- **Culture: Promote a forward-thinking culture, planning for the future, not just for the present.**

Despite the pace of day-to-day manufacturing business operations, strategic planning is essential in times of rapid change. Strategic planning positions manufacturing businesses to remain relevant and improve their competitive standing in the mid-to-long term, have a sustainable path to growth and withstand any unexpected challenges with minimal impact on growth.

The manufacturing sector is no outlier in the global business environment in experiencing a significant acceleration in its pace of business.

Various factors, including technological advancements, international competition, and evolving customer demands, drive this. The dominant mode of business of the past, featuring lengthy production cycles, rigid processes, and time-consuming strategic planning activities, is challenged by a need for agility and responsiveness directly impacting strategic planning. Manufacturers must avoid falling into the trap of merely reacting to outside stimuli and foregoing strategic planning as this might seem prudent in the short term to manage day-to-day challenges but jeopardises the organisation's long-term wellbeing.

Developing a mechanism that allows the integration of agile and resilient strategic considerations that align with day-to-day demands will distinguish future leaders from companies facing significant competitive challenges.

Manufacturers are set in a dynamic VUCA world where product lifecycles are shorter, customisation and personalisation are paramount, and complex global supply networks exist. This accelerated pace of business also brings challenges, such as the need for continuous upskilling of the workforce and the potential for job displacement. Manufacturers must navigate these complexities while focusing on quality, sustainability, and ethical practices to ensure long-term success in this fast-paced environment. To navigate this environment, the workforce and leadership must cultivate research, analytics, and critical-thinking skills to develop innovative solutions for pressing challenges while at the same time following a viable business strategy.

To compete and thrive, manufacturers must adopt technologies such as automation, robotics, and artificial intelligence to increase the efficiency and resilience of their operations and allow for rapid adaptation to changing market needs. Especially the integration of AI across all layers of the organisation further amplifies this digital transformation, empowering manufacturers to optimise production, predict maintenance needs, and develop innovative products.

In today's fast-paced manufacturing landscape, fostering and actively encouraging a forward-thinking culture is paramount. It has to be engrained in the culture that simply reacting to current trends is no longer sufficient; manufacturers must proactively anticipate and shape the future through strategic planning. This involves investing in research and development, embracing emerging technologies, and cultivating a workforce that is adaptable to change and sees change as an opportunity. By prioritising long-term vision over short-term gains, manufacturers can position themselves at the forefront of innovation, ensuring resilience and sustained growth in an ever-evolving industry.

5. IMPLEMENT ROBUST RISK MANAGEMENT PRACTICES TO IDENTIFY POTENTIAL THREATS AND DEVELOP CONTINGENCY PLANS

- **Skills: Develop skills in the leadership team and workforce to identify, understand, evaluate, and mitigate risks.**
- **Technology: Leverage analytical technology for predictive analysis and risk assessment.**
- **Culture: Embrace a risk-aware and bold culture that acknowledges and assesses risks, and encourages the development of contingency plans.**

In the VUCA global business environment in which modern manufacturing is set, manufacturers must adopt risk management practices that focus on business continuity and resiliency in the face of disruption and build antifragility capabilities against unexpected future events.

The manufacturing sector is particularly susceptible to disruptions, from sudden shifts in global supply networks and raw material availability demands to geopolitical tensions, black swan events, and technological disruptions. This requires a proactive risk management approach that equips manufacturers to identify potential threats, developments, and events before they escalate. Once identified, manufacturers can develop effective contingency plans and thus build resilience in their operations.

In a first step, this typically includes a comprehensive risk assessment, mapping out potential vulnerabilities across the entire value chain. Dimensions that usually need to be assessed for a manufacturing enterprise include evaluating supplier dependencies, geopolitical risks, cybersecurity threats, natural disasters, transportation and labour issues, and even the potential impact of emerging technologies. By better understanding these risks, manufacturers can prioritise their mitigation efforts and allocate resources effectively. While many agree that it is impossible to predict the future, these assessments serve a second purpose in allowing manufacturers to develop their unique risk map to monitor for indicators relating to their own business.

Once potential threat or disruption indicators have been identified, the next step is to develop robust contingency plans. Contingency plans must outline precise procedures for responding to various disruptions, ensuring that production can continue or be quickly restored with minimal impact on customers and profitability. This might involve diversifying suppliers, maintaining strategic inventory buffers, or establishing alternative manufacturing sites. It must be noted that these contingencies are not designed to be 100% prescriptive, but they need to be designed with unplanned events in mind to provide guidance and structure to resolve the challenge at hand.

In a VUCA world, risk management is not a one-time exercise but an ongoing, deeply engrained process. Hence, developing skilled risk managers in the leadership team and workforce requires understanding that mitigating risk is essential. Employees must continuously monitor the internal and external environment for emerging risks and adjust their strategies accordingly. This requires a culture of vigilance and adaptability, where employees at all levels are empowered to identify and report potential threats.

Leveraging technology, particularly artificial intelligence and data analytics has the potential to enhance risk management capabilities significantly through forecasting and classification.

An AI-powered risk management system may predict specific scenarios early with diverse data, from internal production data to global weather indicators and access to unstructured data from social media. This can give manufacturers the necessary edge in activating mitigation actions and thus make the difference between struggling to run the business and outperforming the competition.

AI's ability to analyse vast amounts of data to identify patterns and predict potential disruptions, while data analytics can provide real-time insights into supply network performance and other critical areas, is directly relevant to risk management. However, this task is not trivial and needs organisational leadership and resource commitment.

Only by implementing robust risk management practices can manufacturers successfully navigate the future VUCA world. How companies respond to change will differentiate between those striving and growing and those eternally struggling to catch up.

6. IDENTIFY AND ADOPT BEST MANUFACTURING PRACTICES TO COVER THE BASICS OF COMPETITIVENESS

- **Skills: Build skills to analyse business processes critically and regularly for the adoption and development of best practices.**
- **Technology: Use processes and technologies that have reliably led to consistent proven outcomes.**
- **Culture: Nurture a culture of best practices focused on their identification, copy, transfer, and translation between business units, and their promotion.**

Today's dynamic manufacturing environment constantly shifts the foundations of competitiveness. To stay ahead of the game, manufacturing companies must dedicate themselves to identifying and implementing the finest practices that will foster operational excellence and innovation. This approach seeks to assist manufacturers in thriving rather than just surviving in a global market where change is happening more quickly.

A manufacturer that has dominated its industry for a long time possesses typically refined production techniques and globally recognised products. However, subtle industry changes can surface as new players enter the market with innovative ideas and more flexible production approaches; rivals may provide comparable quality but at lower prices and faster delivery rates. In response to these emerging challenges, a manufacturing company needs to explore strategies employed by these younger businesses and consider adopting those that contribute to its success.

The first step in this process involves identifying effective practices within and outside the organisation. It all comes down to comparing oneself to the best in the industry, being adaptable, and learning from past successes and failures. This might involve implementing lean manufacturing practices to reduce waste and integrating automation to enhance productivity. The key is identifying what makes a practice 'best' and tailoring it to fit the company's unique strengths and challenges.

Adopting best practices should include more than decisions made by top and middle management. It requires establishing an environment at work where every employee is motivated to offer recommendations for continuous improvements. For instance, employees on the assembly line need to be encouraged to disclose any small inefficiencies they observe, and management should always be ready to hear them out and respond accordingly.

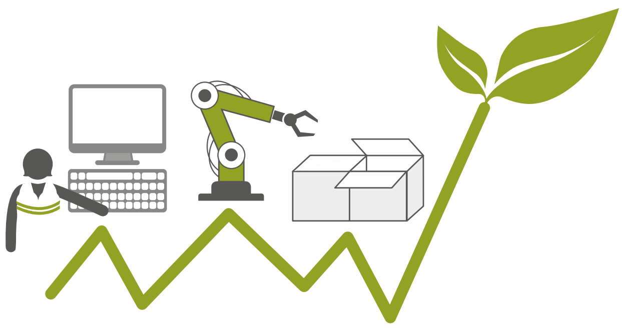
Furthermore, technology is essential to this development. Even though a manufacturing company may spend money on cutting-edge machinery and advanced software, these assets pay off when they streamline current business processes. Modern technology combined with tried-and-true business strategies can take a manufacturer from adequate to outstanding.

Ultimately, the actual industrial transformation starts when a manufacturing company incorporates best practices into its fundamental operations. The entire organisation then develops a culture of constant growth rather than resting on past accomplishments. By taking the initiative and being proactive, manufacturers ensure that they stay one step ahead of their competition, being able to adjust to shifting market conditions and hold onto their competitive advantages.

Likewise, encouraging an environment where best practices are valued can spark creativity in unexpected directions. Allowing each leader and worker to exercise critical thought about how their job might be improved can foster small-scale breakthroughs that can significantly improve productivity and product quality over time.

Lastly, integrating best practices must be viewed as an ongoing process instead of a one-time endeavour. The procedures that define a competitive manufacturer's successful business operations should change along with its market and technological advancements. By dedicating themselves to this continuous improvement process, manufacturers may guarantee their survival and sustained success in an increasingly competitive global market.

7. APPRECIATE SUSTAINABILITY AS A MANUFACTURING BUSINESS OPPORTUNITY RATHER THAN PREDOMINANTLY A CHALLENGE



- **Skills: Foster green innovation skills in the workforce to identify and exploit opportunities to generate value from green products, services, processes, or business models.**
- **Technology: Use green technologies and processes to mitigate environmental impacts, comply with regulations, and adapt to new customer expectations.**
- **Culture: Inspire a culture of green innovation focused on the design, engineering, and (re-) manufacturing of environmentally friendly products across their lifecycle.**

Sustainability is an imperative topic that concerns everyone, manufacturers and their consumers worldwide, out of necessity. Everyone shares this planet with finite resources and must ensure they are preserved for future generations. While most people agree with this sentiment, it sometimes conflicts with the traditional perception of conducting business and manufacturing products that consume finite (raw) materials, energy, and water as production resources. At the same time, a growing world population is becoming accustomed to an unsustainable, consumption-based lifestyle, thus placing even more pressure on already limited resources.

On this planet under constant environmental pressure, manufacturing companies seem to face an impossible challenge: satisfying the ever-growing customer demand and successfully navigating the global competitive landscape, all while adhering to sustainability practices.

Consequently, everyone must acknowledge to manufacturers and their customers that these sustainable manufacturing and consumption challenges exist. However, these challenges also present a significant, primarily untapped opportunity. For example, with a rising demand for eco-friendly products by (green) consumers worldwide, their global market represents a tremendous business opportunity to create new competitive advantages based on sustainable product designs and manufacturing practices. Consumers are more environmentally conscious and willing to spend more on products that reflect their green values. Nevertheless, there is a catch: these green consumers are largely educated and critical thinkers. So, short-term and superficial solutions such as marketing-based greenwashing are no longer well received. We call on products, their manufacturers, and supply chains to ensure sustainable design, manufacturing, and logistics practices and build trust through transparency and openness.

In this context, technology is playing an increasing role in fostering sustainable manufacturing ecosystems. For example, blockchain technology enables manufacturing companies and their supply chains to provide item-level tracking of sustainably sourced and manufactured products. Moreover, technology makes it possible to offset one's carbon footprint from consumption, manufacturing, and logistics, from quantifying the carbon footprint to drive less mitigation through blockchain-verified and certified carbon credits available on the marketplace.

Another factor is the increasing pressure on manufacturers from financial institutions and policymakers to adhere to sustainability practices. While often seen as restrictive and hampering flexibility and growth, it is an opportunity to take a step back and critically assess inefficiencies and other areas for improvement. Today's industrial production globally still has significant potential to reduce energy consumption in unison with inefficiencies to improve productivity. In many cases, trying to improve the energy efficiency of a process leads to substantial productivity gains as well.

Furthermore, using technology to identify opportunities for improving production processes and supply chains, reducing overall resource consumption, and increasing transparency is becoming extremely beneficial. This fundamental approach has been engrained in the engineering mindset for decades; however, adding the sustainability dimension as an opportunity is a game-changer.

This opportunity's potential positive business impact, presented by adopting sustainability practices more broadly, is significant. It extends beyond the fundamental competitive key performance indicators, and in the war for talent and skilled labour, any organisation that has embraced sustainability as a core value has a leg up on the competition in attracting top talent globally. Overall, in the past decades, the awareness has risen that competitive manufacturing and sustainability must go hand in hand, and this cultural shift inspires the most sought-after talent first, amplifying the positive impact over the long term.

8. EXPLORE NEW MANUFACTURING TECHNOLOGIES THAT CAN SUPPORT THE DIGITAL-GREEN TRANSITION

- **Skills: Put forward and integrate digital and green workforce skills for achieving net-zero goals.**
- **Technology: Leverage digital technologies for materials-, energy-, and water-efficiency smart and sustainable manufacturing systems.**
- **Culture: Create a hybrid culture passioned about digital and green literacy to sustainably reshape manufacturing systems.**

In lockstep with the need to perceive sustainability as an opportunity comes the necessity to innovate and explore new manufacturing technologies to support the accelerating digital-green transition.

These manufacturing technologies are understood as being a broad category, encompassing modern digital technologies, such as 5G and cloud computing, and new manufacturing processing technologies, such as 3D printing for lightweight structural components. Overall, in the global manufacturing competitive arena calling for advancing digitalisation and fostering sustainability, new digital and green technologies offer manufacturers the opportunity to support a digital-green transition to smart and sustainable (green) manufacturing systems.

When discussing new digital and green manufacturing technologies, the skills gap is almost certainly a significant concern for all manufacturers. Continuously developing and encouraging the adoption of digital skills and literacy across the workforce and leadership team and investing in training on the benefits of a green transition (green skills) is a crucial enabler towards achieving net-zero goals in manufacturing processes and supply chains.

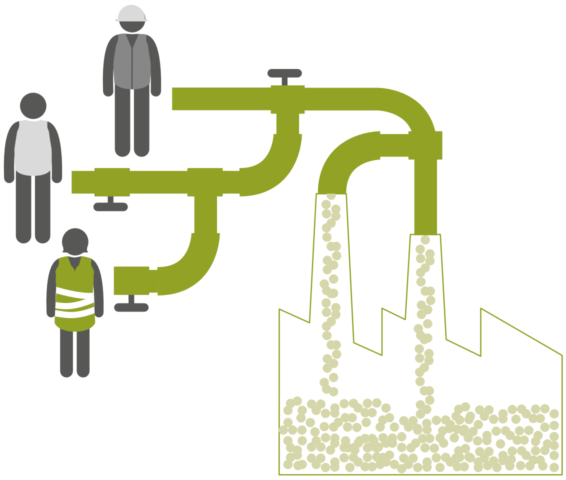
Innovation in manufacturing processing technology enables the processing of new materials with desirable sustainability properties like being (bio-)degradable and lightweight and new opportunities to reinvent traditional supply chains. Such is the case of additive manufacturing (AM) technologies that can reduce the need to transport urgently needed spare parts via aircraft by producing these locally and on-demand, thus reducing their associated transport-related carbon footprints. Furthermore, downtime or inefficient use of AM machine tools can be reduced with advanced digital technologies like IIoT (Industrial Internet of Things) sensor systems connected through 5G networks for monitoring purposes.

Most current manufacturing processes offer the potential to increase their efficacy in one or more dimensions, such as energy, water, or some other resource efficiency. Innovative digital technologies play a crucial role in unleashing this massive potential by provisioning the process data, the tools to derive insights from the data, and the technologies to host, run, and distribute the insights gained, as well as the mechanisms to put them into action.

To date, many manufacturing initiatives are limited to concrete targeted improvements. To fully embrace new manufacturing technologies' digital and green capabilities and reap their rewards, the corporate mindset needs to change towards deploying new technologies with multiple objectives in mind where feasible, such as digital and green ones.

This way, the expensive data collection efforts and information and communication infrastructure can be utilised for various improvements. In many cases, over the term of a project deploying new manufacturing technologies, new opportunities arise from the initial insights gained. When these opportunities are met with a digital-green mindset, organisations can doubly capitalise on them and advance rapidly towards a more sustainable and competitive future.

9. INVEST IN BUILDING A TALENT PIPELINE AND DEVELOPING FUTURE LEADERS FOR A STRONG MANUFACTURING SECTOR



- **Skills: Aim not only for new skills learning but also for their practice to create impact and for them to be perfected.**
- **Technology: Take advantage of technology to enhance workforce planning & talent management with talent analytics.**
- **Culture: Encourage a culture of continuous learning and knowledge-sharing in and among the leadership team and workforce.**

A vibrant production line, humming with the sounds of gears and the energy of a well-organised team of workers, is where seasoned pros and eager newcomers add to a legacy of quality and creativity. However, as manufacturing industries change and veterans retire, there is a good chance that this passion and productivity could fade away. This hypothetical situation powerfully highlights the significance of a resolute dedication to nurturing the potential of the upcoming workforce generation – a vision for guaranteeing a successful future.

A company's workforce might be just as responsible for its decades-long success as its cutting-edge technology or dominant market position. According to the leadership, every individual in the organisation has potential, from the manufacturing shop floor to the boardroom. They understand that the individuals who operate machinery and innovate with processes and materials are the true architects of the manufacturing sector's future rather than just the tools or materials themselves.

A young, enthusiastic technician who joins a manufacturing company without prior experience may be seen as a simple worker and a future leader. In an organisation that genuinely invests in its future workforce, this technician is nurtured, challenged with complex projects, and provided with solid mentorship. With time, this individual develops into a visionary leader who can guide the company through impending industry issues. This talent- development process may be compared to planting seeds in a garden, which, given the right conditions and care, develop into robust, resilient plants that provide fruit for many years.

Technology is a critical component in this talent-development process pipeline. Manufacturing companies can predict the talents their future leaders will need and ensure those capabilities are being developed today by utilising technologies like talent analytics. Talent analytics acts as an organisation's roadmap, pointing out the proper route and assisting leaders in avoiding potential talent risks. However, it is essential to remember that the people, their ultimate leadership and growth, remain at the centre of this vision.

Lastly, it goes beyond satisfying and sustaining short-term commercial demands to foster future leadership and talent in the manufacturing sector. It is about laying a solid basis for the sector's long-term (social) prosperity. Competitive manufacturing companies must guarantee that they have the trained staff required to handle the volatility, uncertainty, complexity, and ambiguity of tomorrow's industrial landscape by promoting continuous learning and providing avenues for career progression.

Sustaining a competitive edge in the manufacturing sector requires creating a robust talent pipeline. People are the real asset of this investment, the future leaders who will spur innovation, adjust to shifting market conditions, and preserve the sector's tradition of excellence rather than just technology or procedures. By fostering this talent now, manufacturers can ensure their position at the forefront of their industries for future generations.

The importance of mentorship and ongoing growth in a constantly changing field must be considered. Experienced professionals possess a great deal of information and expertise that, when disseminated, can influence the outlook and competencies of the upcoming generation. The gap between experience and innovation may be closed by developing formal mentoring programmes prioritising knowledge transfer. This will help ensure that the sector's record of excellence is perpetuated and stays robust in the face of upcoming difficulties.

10. BUILD STRATEGIC PARTNERSHIPS TOWARDS A COOPETITIVE MANUFACTURING BUSINESS ECOSYSTEM

- **Skills: Cultivate in the leadership team coopetition skills to make relevant strategic choices that balance collaboration and competition.**
- **Technology: Support coopetition choices with decision-support systems to better understand their risks, impacts, and expected outcomes.**
- **Culture: Spark a healthy competition culture and propel win-win strategies.**

In the face of grand manufacturing challenges such as sustainable industrial development, "coopetition" offers a competitive strategy combining the advantages of cooperation and competition to bring positive sustainability outcomes to both the manufacturers involved and society.

The transition to this highly collaborative and competitive model presupposes the need to build new skills, especially regarding managerial functions. It is necessary to have a leadership that knows how to create dynamic and sustainable partnerships over time, seeing the best growth opportunities for one's own company and the entire business ecosystem. A wide-ranging leadership is needed to make decisions based on all available information and be able to design short-, medium-, and long-term scenarios. It is then necessary to have the appropriate skills that allow both managers and executive functions to make the most out of the digital technologies available today and to be able to carefully evaluate the future introduction of new ones to increase the value of collaboration. The creation of a highly cooperative model presupposes the possibility, for all the actors involved, of having information representative of the overall corporate ecosystem, the chance of being able to rely on support for strategic decisions, the ability to manage interactions with one's counterparts and the ability to execute efficiently. Therefore, an organisational model characterised in this way requires a technology adoption strategy that allows the diffusion of capabilities along the entire value chain. This configuration can be made possible by the widespread adoption of Industry 4.0 technologies and best practices currently available. The Industrial Internet of Things (IIoT) technologies enable the building of a digital representation of production assets to ensure their visibility in allocable production capacities. The IIoT also generally allows the digitalisation of all manufacturing processes that use physical assets. Big data allows the collection and storage of large amounts of data and information to accurately represent the events that characterise a value chain and information from organisations' internal systems and the surrounding ecosystem. Artificial Intelligence (AI) and machine learning enable decision support based on available data. These smart algorithms can now be specialised for individual business operation sub-processes, providing essential support. Generative AI provides for the smart automation of tasks that use many human resources, allowing these resources to be freed and scaled, thus reducing costs and execution times.

The interconnection between information management systems enables the automation of transactions. In this scenario, the Cloud represents the central technology that allows digital democratisation by reducing technological debt, especially for smaller companies. From a cultural point of view, it is necessary to activate a profound change in current business and operating models. It is essential to move to models that see growth not as an individual objective but as a shared objective along the value chain, including suppliers and customers. In this sense, if until now, business culture has favoured compartmentalised models, looking at partnerships and the relationship with the supply market tactically and opportunistically, the business and operating models of the future must take charge of the shared construction of a highly coopetitive ecosystem, where opportunities for innovation can be jointly developed. Skills and technologies must become familiar and shared assets within the value chains. All actors must participate in creating collective assets, each with their know-how and investments. In this coopetitive model, institutions and academic bodies must not be lacking, as they must act as facilitators for the creation of such collaborations through the definition of policies that ensure healthy competition and cooperation between companies and the protection of customers, stimulate and incentivise, including economically, the definition of common and shared assets models, and the diffusion of new business culture in their current and new generations of white-collar workers.

Conclusion

The 2024 World Manufacturing Report - New Perspectives for the Future of Manufacturing: Outlook 2030 - has addressed the global manufacturing sector's most relevant trends and tipping points with a horizon towards 2030. It has analysed in depth the (geo)political, economic, social, technological, legal, and environmental driving forces that are shaping and will shape the future of manufacturing in the coming years.

The 2024 World Manufacturing Report has also presented four scenarios for the future of manufacturing beyond 2030, aiming to provide a strategic planning framework for discussion and enable decision-makers to anticipate the upcoming grand manufacturing and supply chain challenges for seizing opportunities more effectively and crafting resilient strategies for an evolving global manufacturing landscape.

As it is tradition, the 2024 World Manufacturing Report has provided 10 Key Recommendations for policymakers and industry leaders on how to futureproof manufacturing operations and supply chains in the face of the sector's present and foreseen volatile, uncertain, complex, and ambiguous (VUCA) business environment.

The 2024 World Manufacturing Report has been supported by high-level industrial, government, and academic representatives to guarantee its international authoritativeness. Thus, the Report serves as a whitepaper on the future of manufacturing by providing a set of scenarios, trends, tipping points, and key recommendations that aim to support economic, social, and environmental prosperity for all through manufacturing.

In the coming years, the global manufacturing sector will have a short window of opportunity before reaching the different "positive" and "negative" tipping topics discussed in this Outlook 2030, so its industries must proactively act, act now, through industrial transformation to shape a positive and sustainable future for manufacturing and its supply chains by re-designing existing and/or designing new products, processes, and systems capable of achieving the triple-bottom-line and guaranteeing resilience in the face of (geo)political, economic, social, technological, legal, and environmental challenges that may emerge in the global manufacturing arena.

We believe this Report will serve as a valuable strategic planning, forecasting, and business intelligence tool for thriving in a VUCA manufacturing world, where challenges must be faced, risks must be proactively managed, and bold decisions must be made to succeed.

Young Manufacturing Leaders

Winning Case Studies on New Perspectives for the Future of Manufacturing: Outlook 2030

YML Contest for the 2024 World Manufacturing Report

Young Manufacturing Leaders is a global initiative for students, young workers and professionals interested in a career in the manufacturing sector.

The YML network is strongly committed to raising awareness of the opportunities in manufacturing, and to spreading knowledge of the skills needed in this sector. It supports members with different activities such as peer-to-peer seminars, mentorships with professionals and entrepreneurs, and participation in the activities of the World Manufacturing Foundation.

From July to September 2024, the YML Contest for the 2024 World Manufacturing Report was held, inviting young leaders from all over the world to submit a case study relevant to the topic of New Perspectives for the Future of Manufacturing: Outlook 2030.

The submissions were evaluated by the World Manufacturing Foundation and the winning case studies are included in this section.

The Young Manufacturing Leaders network initiative, launched in 2020, now has nine partners: Made Competence Center Industria 4.0, Chalmers University of Technology, Czech Technical University in Prague, IMH Campus, Laboratory for Manufacturing Systems & Automation, University College Dublin, University of Porto, Grenoble INP – UGA – Graduate schools of Engineering and Management and the World Manufacturing Foundation.

The initiative is co-funded by the European Union, within the framework of the EIT Manufacturing programme.

For more information, visit youngmanufacturingleaders.org

eit Manufacturing

Co-funded by the European Union

YML

Tackling environmental and socio-economic tipping points in manufacturing: the power of geometric deep learning to overcome labour shortages and automate recycling

Patrick Bründl
Research Associate & PhD Candidate, Friedrich-Alexander-Universität Erlangen-Nürnberg - YML Milan City Hub

Two of the biggest challenges in developed countries are the shortage of skilled workers, especially in technical fields, and achieving the Sustainable Development Goals (SDGs). One way to make progress on the SDGs in manufacturing is to recycle, reuse, or remanufacture electronic devices. The components in these devices are often not all defective, or not defective at all when the entire product is replaced with a technologically superior one. An example of this arecontrol systems used to distribute signals and loads in automation solutions, or power distribution networks. This use case is a prime example of engineer-to-order manufacturing, where competitiveness in a volatile, uncertain, complex, and ambiguous business environment is critical. At the same time, the large number of installed components assembled are designed for thousands of switching cycles and experience only a fraction of these in operation. Meanwhile, the assemblies contain metals such as copper and silver or engineering plastics that contribute significantly to the overall carbon footprint of the device. A life cycle assessment of a sample product in use for 15 years shows that the most significant life cycle phase in terms of abiotic resource use is the raw material extraction phase. This is mainly due to the high consumption of copper and the significant sub-processes of operating copper mines, processing sulphide ore and electrolysing copper. For the climate change impact category, the extraction phase (22.2%) and the use phase (74.8%) contribute the most to the total impact, while production and distribution each contribute less than one percent and disposal only 2.3%. Looking at the climate change category, in addition to the use stage, which is primarily influenced by the electricity mix used, the raw material extraction or component manufacturing stage is of particular importance. This observation highlights the significant impact that recycling can have on the product's environmental profile, drastically reducing climate change-related dimensions.

The issue of skills shortages in the industry is highlighted by a 2023 study, which shows that 74% of all companies in this industry are suffering from an acute shortage of skilled workers and are looking for new ways to recruit them. Since the market is undersupplied, improved hiring practices alone are insufficient. Therefore, efforts are being made to involve semi-skilled workers in the value-added production and assembly steps. For example, in the control cabinet use case, the areas of component placement and electrical wiring are particularly important, accounting for about 66.9% of assembly time. Until now, these steps have been performed almost exclusively by skilled electricians, taking up a large portion of their available time[1].

The similarity between the two tipping points lies in a common challenge: lack of data. Recycling complex, multi-stage products in high-wage countries is hindered by their unsuitability for automated disassembly. These products often arrive in small quantities, lacking essential data or manufacturer information. Consequently, identifying relevant components or joints for robotic disassembly and planning the initial path is difficult, and manually collecting this data is time-consuming and costly[2].

A similar problem arises when training unskilled workers. Most companies still rely on schematic diagrams for cabinet assembly, often available only as lengthy printed documents where wired connections are manually checked off. The challenge of this assembly step lies not in the complexity of the assembly tasks but in interpreting the information provided. However, to implement a worker assistance system, such as optical projection, precise position data of components and joints is required. This is not feasible due to the large number of different electronic and electromechanical components, their manufacturers, varied ECAD programs, and differing data standards[3].

Geometric deep learning for data generation

To access the required assembly-relevant information, geometric deep learning methods can be applied. Unlike traditional deep learning, which is often used with ordered Euclidean data like images, applying it to complex 3D geometries faces challenges such as the curse of dimensionality and the need to transform data without distorting shape or positional information. A promising 2023 study describes a comprehensive data pipeline that can access both the standardised STEP data format and polygon data[4]. This pipeline allows the retrieval of geometric data provided by manufacturers, while also enabling the identification of assembly-relevant features from scanned data based solely on geometric information. The approach was validated with accuracies of up to 0.97 mm on a random sample of 49 components from a dataset of 46,068 electronic components. In addition to the accuracy of the centre points, the alignment of the fixtures is critical for fully automated assembly operations, especially when dealing with flexible elements such as cables. To evaluate this, the angular deviations and the Spherical Boundary Score (SBS) were analysed. Angular misalignment results of up to 3.00 degrees were achieved, and the SBS of up to 1.75 mm was approximately 45% better than the one from the leading ECAD database[5].

Conclusion

The results show that the approach can fully automate the derivation and computation of urgently needed data for both assembly and disassembly, based solely on the external geometric shape of components. Furthermore, the presented technological approach allows this to be done with sufficient accuracy and data quality to validate the described use cases on an industrial scale. The accuracy is sufficient for optical guidance of the worker, making it easy to operate and follow, even for unskilled workers. The accuracy is also high enough for path planning for automated disassembly, providing a solid foundation for full automation using robotics, where optical or force-based adjustment at the end effector can compensate for any remaining tolerances.

References

1 *Bründl, P., Stoidner, M., Bredthauer, J., Nguyen, H. G., Baechler, A., & Franke, J. (2024). Unlocking the potential of digitalization and automation: a qualitative and quantitative study of the control cabinet manufacturing industry. Production & Manufacturing Research, 12(1), Article 2306820. https://doi.org/10.1080/21693277.2024.2306820*

2 *Bründl, P., Scheck, A., Nguyen, H. G., & Franke, J. (2024). Towards a circular economy for electrical products: A systematic literature review and research agenda for automated recycling. Robotics and Computer-Integrated Manufacturing, 87, 102693. https://doi.org/10.1016/j.rcim.2023.102693*

3 *Scheffler, B., Bründl, P., Nguyen, H. G., Stoidner, M., & Franke, J. (2024). A Dataset of Electrical Components for Mesh Segmentation and Computational Geometry Research. Scientific Data, 11(1), 309. https://doi.org/10.1038/s41597-024-03155-w*

4 *Bründl, P., Scheffler, B., Stoidner, M., Nguyen, H., Baechler, A., Abrass, A., & Franke, J. (2023). Semantic part segmentation of spatial features via geometric deep learning for automated control cabinet assembly. Journal of Intelligent Manufacturing. Advance online publication. https://doi.org/10.1007/s10845-023-02267-1*

5 *Bründl, P., Scheffler, B., Straub, C., Nguyen, H. G., Stoidner, M., & Franke, J. (2024). Geometric Deep Learning as an Enabler for Data Consistency and Interoperability in Manufacturing. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4871779*

Leveraging generative AI for smart maintenance: navigating technological tipping points in manufacturing

Siyuan Chen
PhD Student, Chalmers University of Technology - YML Gothenburg City Hub

Today's manufacturing landscape is characterised by constant change, with rapid technological advancements reshaping the industry. Smart maintenance is a critical field for manufacturers in Industry 5.0, offering the ability to forecast potential equipment failures, enabling timely interventions that minimise downtime and provide actionable response strategies.

As we reach a crucial technological tipping point, keeping pace with these emerging technologies is vital for manufacturers to remain competitive in a volatile, uncertain, complex, and ambiguous (VUCA) environment. Leading this technological shift is Generative AI (GenAI), a breakthrough in machine learning and deep learning that generates meaningful content, such as text, images, or audio, based on training data[1]. The industry is now preparing to integrate this transformative tool and apply it to enhance maintenance practices. This paper will explore the opportunities, challenges, existing applications and outlook for leveraging GenAI for smart maintenance.

Opportunities

GenAI offers substantial opportunities for smart maintenance. One key area is anomaly detection, where the lack of anomaly data poses a significant challenge. This issue affects both industrial image anomaly detection and time series anomaly detection. GenAI can address this by augmenting and synthesising data based on existing normal datasets, creating realistic and diverse synthetic data that enriches and fills gaps in the existing datasets. This enhanced data facilitates more accurate anomaly detection, which in turn improves predictive maintenance. Another significant impact of GenAI is in upskilling maintenance workers.

GenAI enhances worker skills through personalised learning, adaptive feedback, and tailored safety training. This approach enables continuous skills development, with GenAI generating realistic scenarios and providing customised guidance. Additionally, by leveraging historical data and real-time analytics, GenAI deepens workers' understanding of equipment and processes, ensuring they perform tasks effectively and safely. The real strength of GenAI is its ability to create a dynamic learning experience, helping workers collaborate with AI systems for more efficient and safer maintenance.

Challenges and barriers

While GenAI offers transformative potential for smart maintenance, its successful implementation is fraught with significant challenges, particularly in terms of cost, resource investment, and data quality[2]. Deploying GenAI solutions for smart maintenance can be very expensive, requiring substantial investment in AI infrastructure, including powerful computing resources and robust data storage. Additionally, the expertise needed to develop and maintain these systems, such as data scientists and AI specialists, is both costly and in short supply. For smaller manufacturers or even larger companies with tight budgets, the financial burden of AI implementation can be overwhelming.

This high barrier to entry often forces companies to rely on outsourced services rather than developing in-house solutions, which can lead to additional costs and potential dependency on external providers.

Also, GenAI's effectiveness depends on vast amounts of high-quality data, which is often difficult to collect, clean, and maintain. Inconsistent or incomplete data, often siloed across departments, can hinder the accuracy of AI-driven maintenance. Fine-tuning models like "Maintenance GPT" requires well-curated datasets that many SMEs and larger companies may struggle to provide. Poor data quality compromises the precision and reliability of smart maintenance solutions.

But the biggest barrier is the uncertainty from the companies. Industries do not really dare to use GenAI at scale because of compliance concerns. Some of them are unsure whether they have the rights to freely use models and the background data that models have been trained on. Also, there are data leaking problems where the confidential data will be trained for the large language models. There is not a clear general law or policy for applying model- and responsibility-related matters. Those kinds of uncertainties lead the maintenance workers to prefer to continue with traditional methods for the time being.

Applications

There are already several GenAI applications that serve smart maintenance in the industry. For instance, Siemens has launched the Senseye predictive maintenance application, a Software-as-a-Service (SaaS) solution that integrates GenAI with machine learning to deliver a comprehensive predictive maintenance strategy[3]. This tool processes data, retrieves similar cases, and provides actionable insights within a secure cloud environment. By contextualising available information and incorporating concise maintenance protocols, Senseye enhances the accuracy and effectiveness of prescriptive maintenance strategies for its users, leading to more informed and timely decision-making.

Additionally, predictive maintenance-related GPT applications have been developed using OpenAI's technology. For example, the Predictive Maintenance Advisor GPT from 1ai.com is designed to understand and analyse data related to machinery, offering predictive insights that help maintenance practitioners optimise their maintenance practices[4]. These tools help anticipate issues, reduce downtime, and extend machinery lifespan. Moreover, ChatGPT can assist in creating detailed maintenance reports by following specific prompts and steps, making it easier for maintenance teams to document and track their activities efficiently[5]. As these technologies continue to evolve, their applications in smart maintenance are likely to become even more sophisticated and integral to industry practices.

Outlook

As we approach 2030, GenAI is expected to be more deeply integrated into autonomous maintenance systems, enabling AI not only to predict and prescribe maintenance actions but also to initiate and execute them with minimal human intervention. The full potential of GenAI in smart maintenance will be realised through more complex applications. We can anticipate the development of advanced prescriptive maintenance systems that utilise a comprehensive range of data, such as machine history, work orders, and real-time sensor inputs to determine the precise type and timing of maintenance required. This evolution represents a technological tipping point where GenAI supports and enhances human decision-making, leading to more resilient and adaptive manufacturing processes.

Conclusion

The paper discusses the opportunities, the challenges that may be faced, the applications that already exist, and the outlook for the future regarding GenAI in the field of smart maintenance. Manufacturers who adopt GenAI will enhance efficiency and maintain a competitive edge in a VUCA environment. Embracing GenAI is essential for fostering innovation and resilience in manufacturing, ensuring that smart maintenance keeps evolving.

References

1 *Feuerriegel, S., Hartmann, J., Janiesch, C., & Zschech, P. (2024). Generative ai. Business & Information Systems Engineering, 66(1), 111-126*

2 *Fui-Hoon Nah, F., Zheng, R., Cai, J., Siau, K., & Chen, L. (2023). Generative AI and ChatGPT: Applications, challenges, and AI-human collaboration. Journal of Information Technology Case and Application Research, 25(3), 277-304*

3 *Siemens. (2023, April 20). Generative artificial intelligence takes Siemens' predictive maintenance solution to the next level. Siemens Press. https://press.siemens.com/global/en/pressrelease/generative-artificial-intelligence-takes-siemens-predictive-maintenance-solution-next*

4 *The 1-AI. (n.d.). The 1-AI | AI-powered solutions for your business. Retrieved August 16, 2024, from https://the1ai.com*

5 *AI for Work. (n.d.). ChatGPT prompt: Technical support specialist customer service - Create a maintenance report. Retrieved August 16, 2024, from https://www.aiforwork.co/prompt-articles/chatgpt-prompt-technical-support-specialist-customer-service-create-a-maintenance-report*

Addressing environmental tipping points through advancements and societal changes

Sandra Jakšić
Master's student, Chalmers University of Technology – YML Gothenburg City Hub

As the planet approaches critical environmental tipping points, the need for rapid transformation towards sustainable practices within the manufacturing industry is increasing. Technological advancements can be used to address these urgent environmental challenges, but a fundamental shift in society, away from consumerism, is also required. This essay explores how manufacturers can trigger positive tipping points with disruptive technological innovation, like autonomous vehicles, which can challenge the need for ownership.

The environmental tipping point

Environmental tipping points are critical thresholds in earth's natural systems that, if crossed, have potentially disastrous and irreversible effects. The tipping points like the Greenland and West Antarctic ice sheets, warm-water coral reefs, the north Atlantic subpolar gyre circulation, and permafrost regions, are at the highest risk of being crossed if the global temperature continues to rise[1]. Triggering these tipping points could have a severe impact on the security of water, food, and energy, potentially leading to societal instability as resources become increasingly scarce.

Global initiatives, like the EU's Green Deal and the Paris Agreement, are driving changes in manufacturing practices to lessen these threats. These efforts emphasise the urgent need to reduce carbon footprints, prompting manufacturers to use green technologies and sustainable material sourcing.

Green technologies, such as electric vehicles, are essential to reducing carbon dioxide emissions, as they provide a promising alternative to conventional vehicles with internal combustion engines. However, the underlying cause of environmental degradation, namely societal behaviour and consumerism, still need to be addressed. In order to reduce environmental impact effectively, a structural change in societal attitudes toward ownership is necessary.

The need for societal structural change

The increase in sales of physical products, including vehicles, significantly contributes to environmental degradation. Advancements like electric vehicles and recycling offer some relief, but as long as the demand for new products continues to rise, so will the need for new raw material and energy-intense processes. A societal shift away from ownership is required to break the cycle of overconsumption.

Although car-pooling and car-sharing services exist, they have not yet surpassed the desire for personal vehicle ownership. Despite widespread awareness of the environmental impact of consumption, many people continue to prioritise ownership and personal convenience over sustainability. It seems that desire outweighs logic, and to achieve widespread adaptation of servitisation, Mobility-as-a-Service must become more desirable and offer greater benefits than owning a car.

Case study: Waymo

Technological advancements, particularly in AI and autonomous vehicles, have the potential to create significant positive tipping points in consumer behaviour. As autonomous vehicles become more prevalent, the economic viability of personal car ownership could decline. This would lead to reduced demand for new vehicles and consequently, a reduction in the environmental impact associated with car production.

A leading example of this transformation is Waymo, with the world's largest fully autonomous, paid ride-hailing service[2]. Available in the Metro Phoenix area, San Francisco, and Los Angeles, this service operates 24/7 with an all-electric fleet of Jaguar I-PACE vehicles, all while eliminating the need for human drivers.

The shift away from personal car ownership, driven by services like Waymo, brings economic benefits in addition to the environmental advantages. Privately owned cars remain parked approximately 95% of the time, occupying valuable urban space and contributing to inefficiencies in vehicle use[3]. In contrast, autonomous vehicles can be in constant operation on the road, optimising availability and utilisation. By offering a cost-effective and convenient alternative, Waymo encourages consumers to reconsider the need for owning a personal vehicle. The transportation solution eliminates the burden of parking, maintenance, and the high upfront costs associated with car ownership. The elimination of human drivers also results in a 40% reduction in operating costs compared to conventional ride-hailing services[4]. Furthermore, the service offers higher personal security compared to public transport, and safety by reducing risks stemming from human error, fatigue, and drunk driving.

As Mobility-as-a-Service grows, it is likely to disrupt the traditional automotive market, where personal car ownership has long been the norm. The industry's shift from selling vehicles to selling travel kilometres will require a fundamental change in business models. Automotive manufacturers are compelled to adapt their products and services, by either in-house development or collaborations, to avoid obsolescence.

Adapting to servitisation

As manufacturers transition from selling physical goods to offering services, they must adapt both their products and processes to meet the evolving demands. This shift requires companies to realign their operations, placing the customer at the centre of their ecosystem. Businesses must ensure that their services seamlessly integrate with and enhance various aspects of the customer's life.

With the shift towards servitisation, the perception of quality is evolving. Traditional markers such as brand reputation and aesthetics are becoming less important, while factors such as convenience, accessibility, and dependability are taking precedence. As the focus moves from physical products to software and service delivery, companies must prioritise prompt, credible and trustworthy services over the traditional tangible quality of their products.

While services present a substantial business opportunity, they also demand a fundamental organisational shift. To successfully adapt to a service-driven model, manufacturers must establish dedicated business units focused on service development and results.

Conclusion

To address the environmental tipping points and remain competitive, manufacturers must harness the synergy between technological advancements and behavioural change. Disruptive technologies, like AI, can create positive tipping points with a shift in consumer behaviour and drive the transition towards more sustainable business models. In doing so, manufacturers will not only contribute to global environmental goals, but also enhance their competitiveness in an increasingly competitive and dynamic market.

References

1 *T. M. Lenton, D.I. Armstrong McKay, S. Loriani, J.F. Abrams, S.J. Lade, J.F. Donges, M. Milkoreit, T. Powell, S.R. Smith, C. Zimm, J.E. Buxton, E. Bailey, L. Laybourn, A. Ghadiali, J.G. Dyke (eds), 2023, The Global Tipping Points Report 2023. University of Exeter, Exeter, UK*

2 *Autonomous Driving Technology - Learn more about us - Waymo. (n.d.). https://waymo.com/about/*

3 *Haupt, A. (2021). From Automotive Industry to Robotaxi Industry: The biggest transformation in automotive since the horse became horsepower? Industrifonden. https://industrifonden.com/wp-content/uploads/2022/12/From-Automotive-to-Robotaxi_20211214-1.pdf*

4 *Ibid*

:YML

Preparing manufacturing leaders to navigate social and environmental tipping points

Miran Ghafoori
EIT Manufacturing Masters student, Aalto University/TU Vienna - YML Gothenburg City Hub

As the manufacturing industry faces a rapidly evolving future, how can companies stay competitive and navigate the challenges foreseen? The answer lies in better strategy and data-driven decision-making. Looking ahead to 2030, the industry faces social tipping points, such as shifting workforce demographics and widening skills gaps. There are also environmental tipping points like the urgent need to meet ESG regulations, which not only present challenges but also create new job opportunities. How well trained are leaders to handle these changes? Can business simulation games offer a solution by bridging the skills gap by providing decision-makers with a sandbox to test their strategies in a real-world scenario? This report explores how manufacturers can address both social and environmental tipping points through business simulation games.

The impact of social and environmental tipping points on the future of work

Job roles are evolving significantly due to advancements in technology, changing demographics, and the green transition. An ageing workforce and migration are leading to labour shortages and skills mismatches. It is projected that the proportion of people aged 65 and over in the European Union will increase to 30% by 2050[1]. In the United States, one in every five residents will be at retirement age by 2030[2]. These demographic changes directly impact the economy. According to OECD predictions, annual GDP growth in its member countries could decline by 0.5 percent by 2030 due to working-age population decline. Therefore, continuous education and upskilling of the workforce are essential — not only to stay ahead of technological trends but also to improve employee retention and attract top talent. Inclusion efforts targeting 55-64-year-olds, as well as women and migrants who are underrepresented groups, will be needed to mitigate labour shortages. Furthermore, the demand for new skills and job roles is driven by green and digital transitions. According to the World Economic Forum's Future of Jobs Report 2023, sustainability and renewable energy specialists are among the fastest-growing roles, and analytical and creative thinking remain the most important skill.

Diverse teams and simulation games

Teams with knowledge across multiple disciplines can approach problems from various perspectives, leading to more innovative solutions. A diverse skill set also makes employees more adaptable to changing job requirements and industry trends. A 2018 study by Boston Consulting Group found that companies with diverse leadership teams generate 19% higher innovation revenues compared to those with below average diversity. One solution for adapting to evolving job roles lies in educational business simulation games. Participants practice strategic decision-making and problem-solving through managing a production company, helping them develop a holistic understanding of business operations.

Research shows promising outcomes

Business simulation games are among the most effective and risk-free tools for training and upskilling, offering significant cognitive, behavioural, and affective learning outcomes. According to a systematic review by Vlachopoulos & Makri (2017)[3], these games enhance learning by engaging participants in interactive, real-world scenarios. For example, Palmunen et al. (2021)[4] demonstrated that after participating in simulation sessions by RealGame.fi, the complexity of users' mental models increased. Additionally, the percentage of students with misconceptions dropped significantly.

How RealGame[5] simulates real-world scenarios

In aviation, simulators allow pilots to train without the danger and cost of real-world mistakes. Similarly, Real Game provides a safe space for learning to navigate complex scenarios. Participants work in teams of 2-5, with roles such as Production Manager, Procurement and Logistics, or they may share responsibilities. The goal is to maintain balanced operations, profitability and sustainability while adapting to evolving challenges. The game begins with pre-set conditions, and as the simulation progresses, teams must make informed decisions to navigate real-world scenarios, such as:

- **Supply chain disruptions:** These are introduced as unexpected challenges to test resilience and adaptability.

For example, if purchased items are not arriving on time, production costs will increase, directly impacting various company KPIs such as production costs, product delivery, and inventory turnover. Some potential solutions are to choose suppliers with higher costs, increased warehousing capacity or more accurate deliveries during disruption times and reduce working production shifts to reduce costs. The teams who will be able to take the hints on time and adapt effectively to these challenges will be winners.

- Investment decisions: As teams progress, they must make strategic decisions regarding investments in R&D for launching new products and entering new markets. In practice, these decisions are typically more complex and require input from various departments, including sales, production, product development, and sustainability. Managers primarily make these decisions as they involve allocating resources to different projects, which can significantly impact on key financial metrics such as Return on Investment (ROI) and profitability (Sales Revenue, Operating Profit).

- Process automation: As the game accelerates, process automation tools like automated customer delivery and raw material procurement systems become available for teams to invest in. These tools help teams learn how to set reorder points and select suitable suppliers based on price, delivery time, payment terms, and delivery accuracy. A startup that wants to outsource manufacturing, increase production, and install an ERP system, for instance, can learn the pros and cons of this kind of shift by implementing their strategy in a simulation game.

- Sustainability metrics: Teams must manage choices that have an impact on sustainability KPIs, such as energy use, waste production, carbon emissions, and the use of sustainable materials. For instance, switching to a cloth composed of recycled materials that is more sustainable. While this aligns with environmental goals and meets the growing consumer demand for transparency, it also poses practical difficulties. The shift could involve higher upfront costs and require significant changes to the manufacturing process.

Figure 1

A real-time dashboard tracks KPIs, allowing teams to adjust strategies and learn from their performance.

(Image by Freepik)

Work in progress...

Simulation games could be further tailored to training in the manufacturing industry by incorporating circular business models, advanced manufacturing technologies, and AI. By integrating circular business models into simulation games, players can gain hands-on experience in building products for longevity and implement strategies for reuse and re-furbishing[6]. Furthermore, with the inclusion of advanced manufacturing technologies, such as 3D printing, players can see their advantages and measure how these technologies reduce costs and demand new skill sets. For example, using 3D printing can enable on-demand production and waste reduction, and increase customer satisfaction. AI systems can enhance learning experiences and provide personalised and automated assessments for facilitators. It is currently the focus of my master's thesis at RealGame.

Conclusion

In a rapidly evolving future, manufacturing industries can stay competitive by understanding and addressing the implications of the tipping points foreseen. Statistical projections show demographic changes, and environmental regulations will significantly affect future workplaces and economies. Future manufacturing leaders must be able to navigate complex problems and understand the impact of their decisions. Business simulation tools have proven to be useful resources that can bridge the gap between strategy and execution through experiential learning. By leveraging these tools, we can develop the required mentality and skill set in leaders to comprehend and address the economic impact of social and environmental tipping points.

References

1 *European Commission. (n.d.). Ageing Europe - statistics on population developments. Eurostat Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Ageing_Europe_-_statistics_on_population_developments#Older_people_.E2.80.94_population_overview*

2 *Vespa, J., Medina, L., & Armstrong, D. M. (2020). Demographic turning points for the United States: Population projections for 2020 to 2060 (Report No. P25-1144). U.S. Census Bureau. https://www.census.gov/library/publications/2020/demo/p25-1144.html*

3 *Vlachopoulos, D., & Makri, A. (2017). The effect of games and simulations on higher education: a systematic literature review. International Journal of Educational Technology in Higher Education, 14, 22. https://doi.org/10.1186/s41239-017-0062-1*

4 *Palmunen, L.-M., Lainema, T., & Pelto, E. (2021). Towards a manager's mental model: Conceptual change through business simulation. The International Journal of Management Education, 19, 100460. https://doi.org/10.1016/j.ijme.2021.100460*

5 *RealGame. (2024). Homepage. RealGame.fi https://www.realgame.fi/*

6 *2023 World Manufacturing Report: New Business Models for the Manufacturing of the Future*

References

1 Gladwell, M. (2000). The Tipping Point: How Little Things Can Make a Big Difference.

2 Adapting the Global Tipping Points. Retrieved from https://global-tipping-points.org/introduction/key-concepts/23

3 Milkoreit, M. et al. (2018). Defining Tipping Points for Social-Ecological Systems Scholarship—An Interdisciplinary Literature Review. Environmental Research Letters, Vol. 13, No. 3, p. 033005.

4 Adapting the Global Tipping Points. Retrieved from https://global-tipping-points.org/introduction/key-concepts/

5 Adapting the Global Tipping Points. Retrieved from https://global-tipping-points.org/introduction/key-concepts/

6 Chen, J. (2024). Trade Wars: History, Pros & Cons, and U.S.-China. Retrieved from https://www.investopedia.com/terms/t/trade-war.asp

7 UNCTAD (2024). Key Statistics and Trends in Trade Policy 2023. Retrieved from https://unctad.org/publication/key-statistics-and-trends-trade-policy-2023

8 Urata, S. (2019). US-Japan Trade Frictions: The Past, the Present, and Implications for the US-China Trade War. Retrieved from https://onlinelibrary.wiley.com/doi/full/10.1111/aepr.12279

9 Shan, W. (2019). The Unwinnable Trade War: Everyone Loses in the U.S.-Chinese Clash—but Especially Americans. Retrieved from https://www.foreignaffairs.com/articles/asia/2019-10-08/unwinnable-trade-war

10 Li, C., Whalley, J. (2021). Trade Protectionism and US Manufacturing Employment. Economic Modelling, Vol. 96, pp. 353-361.

11 The Economist (2024). Europe Prepares for a Mighty Trade War: Will it be Able to Stick to its Rule-Abiding Principles? Retrieved from https://www.economist.com/finance-and-economics/2024/07/11/europe-prepares-for-a-mighty-trade-war

12 Verhelst, K. et al. (2024). Is the EU already in a Trade War with China? Retrieved from https://www.politico.eu/article/china-beijing-market-eu-trade-war-investigation-imports-goods/

13 European Council. EU Sanctions Against Russia Explained. Retrieved from https://www.consilium.europa.eu/en/policies/sanctions-against-russia/sanctions-against-russia-explained/

14 Taran, S. (2024). Cost of Aggression: EU Sanctions Against Russia Two Years On. Retrieved from https://www.epc.eu/en/Publications/Cost-of-aggression-EU-sanctions-against-Russia-two-years-on~58f570

15 Kohonen, I. (2023). Sanctions Against Russia: What have been the Effects so far? Retrieved from https://www.economicsobservatory.com/sanctions-against-russia-what-have-been-the-effects-so-far

16 EU Sanctions Map (26.07.2024). Retrieved from https://sanctionsmap.eu/

17 UNCTAD (2024). Merchandise: Total Trade and Share, Annual. Retrieved from https://unctadstat.unctad.org/datacentre/dataviewer/shared-report/10d987f7-0ade-46e7-b192-f2c24f770be5

18 UNCTAD (2024) Key Statistics and Trends in Trade Policy 2023, 26 Mar 2024, https://unctad.org/system/files/official-document/ditctab2024d2_en.pdf

19 WTO (1996). Participation of Developing Countries in World Trade: Overview of Major Trends and Underlying Factors. Retrieved from https://www.wto.org/english/tratop_e/devel_e/w15.htm

20 UNCTAD. Introduction to NTMs. Retrieved from https://unctad.org/topic/trade-analysis/non-tariff-measures/NTMs-Introduction

21 UNCTAD (2024). Key Evolutions in Trade and Development over the Decades. Retrieved from https://unctad.org/news/key-evolutions-trade-and-development-over-decades

22 WEF (2023). Economic Decoupling? 3 Experts Caution on What that Means for the Global Economy. Retrieved from https://www.weforum.org/agenda/2023/06/global-economic-decoupling-derisking-experts-explain/

23 Riecke, T. (2020). Resilience and Decoupling in the Era of Great Power Competition. Retrieved from https://merics.org/en/report/resilience-and-decoupling-era-great-power-competition

24 TIC Data. Major Foreign Holders of Treasury Securities. Retrieved from https://ticdata.treasury.gov/Publish/mfh.txt

25 CATO (2023). The High Costs of a "Hard" Decoupling from China. Retrieved from https://www.cato.org/blog/high-costs-hard-decoupling-china

26 European Commission. (2023). Speech by President von der Leyen on EU-China Relations to the Mercator Institute for China Studies and the European Policy Centre. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/speech_23_2063

27 Atlantic Council (2024). Ursula von der Leyen set Europe's 'De-risking' in Motion. What's the Status One Year Later?" Retrieved from: https://www.atlanticcouncil.org/blogs/new-atlanticist/ursula-von-der-leyen-set-europes-de-risking-in-motion-whats-the-status-one-year-later/

28 Riecke, T. (2020). Resilience and Decoupling in the Era of Great Power Competition. Retrieved from https://merics.org/en/report/resilience-and-decoupling-era-great-power-competition

29 Demarais, A. (2024). The Winners from U.S.-China Decoupling. Retrieved from https://foreignpolicy.com/2024/07/15/china-decoupling-derisking-emerging-markets-malaysia-mexico-economy/

30 Thompson, J. (2023). Why is Cyber Security a Big Risk to Manufacturers? Retrieved from https://www.nwcrc.co.uk/post/manufacturers-cyber-attacks

31 Wolf, A. (2024). The Top 10 Manufacturing Industry Cyber Attacks. Retrieved from https://arcticwolf.com/resources/blog/top-8-manufacturing-industry-cyberattacks/

32 ChainAlysis (2024). Ransomware Payments Exceed $1 Billion in 2023, Hitting Record High After 2022 Decline. Retrieved from https://www.chainalysis.com/blog/ransomware-2024/

33 Search Logistics (2024). Ransomware Statistics: How Bad are Ransomware Attacks in 2024? Retrieved from https://www.searchlogistics.com/learn/statistics/ransomware-statistics/

34 Goldman Sachs (2023). Resource Realism: The Geopolitics of Critical Mineral Supply Chains. Retrieved from https://www.goldmansachs.com/insights/articles/resource-realism-the-geopolitics-of-critical-mineral-supply-chains

35 iea (2023). Critical Minerals Market Sees Unprecedented Growth as Clean Energy Demand Drives Strong Increase in Investment. Retrieved from https://www.iea.org/news/critical-minerals-market-sees-unprecedented-growth-as-clean-energy-demand-drives-strong-increase-in-investment

36 Pryke, S. (2017). Explaining Resource Nationalism. Global Policy, Vol. 8, pp. 474-482.

37 Eiti (2022). How the Global Pandemic has Shaped Resource Nationalism. Retrieved from https://eiti.org/blog-post/how-global-pandemic-has-shaped-resource-nationalism

38 European Commission (2024). Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials. Retrieved from https://eur-lex.europa.eu/eli/reg/2024/1252/oj

39 Energy.gov (2022). Inflation Reduction Act of 2022. Retrieved from https://www.energy.gov/lpo/inflation-reduction-act-2022#:~:text=The%20President's%20Inflation%20Reduction%20Act,energy%20manufacturing%2C%20and%20putting%20the

40 Sovereign. Cambridge Dictionary. Retrieved from https://dictionary.cambridge.org/da/ordbog/engelsk/sovereign

41 VDE. Technological Sovereignty: Methodology and Recommendations. Retrieved from https://www.vde.com/resource/blob/2013656/66f71138ba34b7b3ad0e2aa248b71abd/vde-position-paper-technological-sovereignty-data.pdf

42 Edler, J. et al. (2023). Technology Sovereignty as an Emerging Frame for Innovation Policy. Defining Rationales, Ends and Means. Research Policy, Vol. 52, Issue 6, p. 104765.

43 Energy.gov (2022). Inflation Reduction Act of 2022. Retrieved from https://www.energy.gov/lpo/inflation-reduction-act-2022#:~:text=The%20President's%20Inflation%20Reduction%20Act,energy%20manufacturing%2C%20and%20putting%20the

44 European Parliament Think Tank (2022). EU Strategic Autonomy 2013-2023: From Concept to Capacity. Retrieved from https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)733589

45 Edler, J. et al. (2023). Technology Sovereignty from Demand to Concept. Retrieved from https://www.isi.fraunhofer.de/content/dam/isi/dokumente/publikationen/technology_sovereignty.pdf

46 Fraunhofer IZM. Technological Sovereignty to Counter Micro-chip Shortage. Retrieved from https://www.izm.fraunhofer.de/en/news_events/tech_news/technological-sovereignty-to-counter-micro-chip-shortage.html

47 European Parliament Think Tank (2021). Key Enabling Technologies for Europe's Technological Sovereignty. Retrieved from https://www.europarl.europa.eu/thinktank/en/document/EPRS_STU(2021)697184

48 The Whitehouse (2022). Critical and Emerging Technologies List Update. Retrieved from https://www.whitehouse.gov/wp-content/uploads/2022/02/02-2022-Critical-and-Emerging-Technologies-List-Update.pdf

49 European Commission. Statement on Technological Sovereignty. Retrieved from https://eic.ec.europa.eu/document/download/61d52ef5-5b28-4c00-bfb8-a67e9c22666f_en

50 Edler, J. et al. (2023). Technology Sovereignty as an Emerging Frame for Innovation Policy. Defining Rationales, Ends and Means. Research Policy, Vol. 52, Issue 6, p. 104765.

51 Kalodimos, J. (2024). Financial Disclosure under Regulatory Fragmentation. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4785824

52 Kalmenovitz, J. Regulatory Fragmentation. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3802888

53 Xu, H. (2024). Regulatory Fragmentation and Internal Control Weaknesses. Journal of Accounting and Public Policy, Vol. 44, p. 107191.

54 Guthrie, R. (2018). How Can Fragmented International Regulations Affect Your Business? Retrieved from https://www.forbes.com/councils/

References

forbesfinancecouncil/2018/11/13/how-can-fragmented-international-regulations-affect-your-business/

55 IIF (2018). Addressing Regulatory Fragmentation to Support a Cyber-Resilient Global Financial Services Industry. Retrieved from https://www.iif.com/portals/0/Files/private/iif_cyber_reg_04_25_2018_final.pdf

56 EY (2024). 2024 Geostrategic Outlook. Retrieved from https://www.ey.com/en_nl/geostrategy/2024-geostrategic-outlook

57 IAAP. Global AI Law and Policy Tracker. Retrieved from https://iapp.org/media/pdf/resource_center/global_ai_law_policy_tracker.pdf

58 The Whitehouse (2023). Executive Order on the Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence. Retrieved from https://www.whitehouse.gov/briefing-room/presidential-actions/2023/10/30/executive-order-on-the-safe-secure-and-trustworthy-development-and-use-of-artificial-intelligence/

59 Sheehan, M. (2023). China's AI Regulations and How They Get Made. Retrieved from https://carnegieendowment.org/research/2023/07/chinas-ai-regulations-and-how-they-get-made?lang=en

60 Romero, D. et al. (2023). 2023 World Manufacturing Report: New Business Models for the Manufacturing of the Future. Retrieved from https://worldmanufacturing.org/report/report-2023-new-business-models-for-the-manufacturing-of-the-future/

61 Forbes. (2023). Apple to Diversify its Supply Chain by Producing MacBooks in Vietnam. Retrieved from https://www.forbes.com/sites/qai/2023/01/01/apple-to-diversify-its-supply-chain-by-producing-macbooks-in-vietnam/

62 Galluccio, A., Agrell, P.J. (2022). Industry 4.0 in Focus: The Adidas Speedfactory. Université Catholique de Louvain, pp. 21-32.

63 Hamilton, J. D. (2009). Causes and Consequences of the Oil Shock of 2007-08. Retrieved from https://www.brookings.edu/wp-content/uploads/2016/07/2009a_bpea_hamilton-1.pdf

64 Vakil, B., Linton, T. (2021). Why We're in the Midst of a Global Semiconductor Shortage. Harvard Business Review.

65 History.com. Energy Crisis (1970s). Retrieved from https://www.history.com/topics/1970s/energy-crisis

66 ShipUWL (2020). IMO 2020 and its Impact on the Freight Market. Retrieved from https://blog.shipuwl.com/imo-2020-impact-freight-market

67 Taiwan News (2021). Taiwan to Set Up Chip Plants in Lithuania. Retrieved from https://taiwannews.com.tw/news/4399466

68 International Monetary Fund (2014). Back to Basics: What is Money? Retrieved from https://www.imf.org/external/pubs/ft/fandd/2014/09/basics.htm

69 United Nations. Shifting Demographics. Retrieved from https://www.un.org/en/un75/shifting-demographics

70 The Manufacturer (2024). Demographic trends in the manufacturing workforce. Retrieved from https://www.themanufacturer.com/articles/demographic-trends-in-the-manufacturing-workforce/

71 World Bank Group. Fertility Rate, Total (Births per Woman). Retrieved from https://data.worldbank.org/indicator/SP.DYN.TFRT.IN?end=2022&start=1960&view=chart

72 Yuan Sun, I. (2017). The World's Next Great Manufacturing Center. Retrieved from https://hbr.org/2017/05/the-worlds-next-great-manufacturing-center

73 United Nations. Shifting Demographics. Retrieved from https://www.un.org/en/un75/shifting-demographics

74 Our World of Data. Women's Employment. Retrieved from https://ourworldindata.org/female-labor-supply

75 United Nations. Women's Job Market Participation Stagnating at Less than 50% for the Past 25 years, Finds UN Report. Retrieved from https://www.un.org/en/desa/women%E2%80%99s-job-market-participation-stagnating-less-50-past-25-years-finds-un-report

76 Our World of Data. Women's Employment. Retrieved from https://ourworldindata.org/female-labor-supply

77 Brynjolfsson, E. et al. (2020). The Productivity J-Curve: How Intangibles Complement General Purpose Technologies. NBER Working Paper, p. 25148.

78 Rikala, P. et al. (2024). Understanding and Measuring Skill Gaps in Industry 4.0 — A Review. Technological Forecasting and Social Change.

79 WEF. Reskilling Revolution. Retrieved from https://initiatives.weforum.org/reskilling-revolution/home

80 WEF (2023). Future of Jobs Report. Retrieved from https://www.weforum.org/reports/the-future-of- jobs-report-2023/

81 WEF (2023). Future of Jobs Report. Retrieved from https://www.weforum.org/reports/the-future-of- jobs-report-2023/

82 European Union (2024). Towards a Skills Revolution: Results of the European Year of Skills. Retrieved from https://year-of-skills.europa.eu/document/download/22bb1aa3-1efe-46af-8a19-f6ca83eccf4f_en

83 European Union (2024). Towards a Skills Revolution: Results of the European Year of Skills. Retrieved from https://year-of-skills.europa.eu/document/download/22bb1aa3-1efe-46af-8a19-f6ca83eccf4f_en

84 Eloundou, T. et al. (2023). GPTs are GPTs: An Early Look at the Labor Market Impact Potential of Large Language Models. Retrieved from https://doi.org/10.48550/arXiv.2303.10130

85 Bailey, M.N. et al. (2023). Machine of Mind: The Case for an AI-Powered Productivity Boom. Retrieved from https://www.brookings.edu/articles/machines-of-mind-the-case-for-an-ai-powered-productivity-boom/

86 ILO (2011). Skills for Green Jobs: A Global View. Retrieved from https://www.ilo.org/publications/skills-green-jobs-global-view

87 Medical News Today (2024). Fear of Change Phobia. Retrieved from https://www.medicalnewstoday.com/articles/fear-of-change-phobia

88 McGrath, J.J. et al. (2023). Age of Onset and Cumulative Risk of Mental Disorders: A Cross-National Analysis of Population Surveys from 29 Countries. The Lancet Psychiatry, Vol. 10, Issue 9, pp. 668-681.

89 Forbes (2024). A Guide to Promoting Mental Health in the Manufacturing Industry. Retrieved from https://www.forbes.com/councils/forbesbusinesscouncil/2024/03/14/a-guide-to-promoting-mental-health-in-the-manufacturing-industry/

90 WEF (2023). Global Parity Alliance: Diversity, Equity and Inclusion Lighthouses. Retrieved from https://www.weforum.org/publications/global-parity-alliance-diversity-equity-and-inclusion-lighthouses-2023/

91 Li, F. et al. (2024). Will Diversity, Equity, and Inclusion Commitment Improve Manufacturing Firms' Market Performance? A Signalling Theory Perspective on DEI Announcements. Production and Operations Management.

92 WEF (2023). Global Parity Alliance: Diversity, Equity and Inclusion Lighthouses. Retrieved from https://www.weforum.org/publications/global-parity-alliance-diversity-equity-and-inclusion-lighthouses-2023/

93 Deloitte and The Manufacturing Institute DEI Study (2021). Beyond Reskilling, Manufacturing's Future Depends on Diversity, Equity, and Inclusion. Retrieved from https://themanufacturinginstitute.org/research/beyond-reskilling-manufacturings-future-depends-on-diversity-equity-and-inclusion/

94 Cambridge Industrial Innovation Policy (2023). Empowering Women in Manufacturing: Unlocking the Potential of Gender-Inclusive Digitalization. Retrieved from https://www.ciip.group.cam.ac.uk/reports-and-articles/empowering-women-in-manufacturing-unlocking-the-potential-of-gender-inclusive-digitalisation/

95 World Bank Group (2024). Gender Strategy 2024-2030: Accelerate Gender Equality to End Poverty on a Liveable Planet. Retrieved from https://www.worldbank.org/en/topic/gender/brief/gender-strategy-update-2024-30-accelerating-equality-and-empowerment-for-all

96 Iqbal, A. et al. (2022). Gender Equality, Education, Economic Growth and Religious Tensions Nexus in Developing Countries: A Spatial Analysis Approach. Heliyon, Vol. 8, Issue 11, p. e11394.

97 Deloitte and The Manufacturing Institute DEI Study (2021). Beyond Reskilling, Manufacturing's Future Depends on Diversity, Equity, and Inclusion. Retrieved from https://themanufacturinginstitute.org/research/beyond-reskilling-manufacturings-future-depends-on-diversity-equity-and-inclusion/

98 WEF (2023). Global Parity Alliance: Diversity, Equity and Inclusion Lighthouses. Retrieved from https://www.weforum.org/publications/global-parity-alliance-diversity-equity-and-inclusion-lighthouses-2023/

99 Deloitte and The Manufacturing Institute DEI Study (2021). Beyond Reskilling, Manufacturing's Future Depends on Diversity, Equity, and Inclusion. Retrieved from https://themanufacturinginstitute.org/research/beyond-reskilling-manufacturings-future-depends-on-diversity-equity-and-inclusion/

100 BCG (2024). It's Time to Highlight the Business Opportunity of DEI Initiatives. Retrieved from https://web-assets.bcg.com/0b/c4/c45a07e54f48ae0dc784667a66dd/bcg-its-time-to-reimagine-diversity-equity-and-inclusion-may-2021-r.pdf

101 Deloitte and The Manufacturing Institute DEI Study (2021). Beyond Reskilling, Manufacturing's Future Depends on Diversity, Equity, and Inclusion. Retrieved from https://themanufacturinginstitute.org/research/beyond-reskilling-manufacturings-future-depends-on-diversity-equity-and-inclusion/

102 NielsonIQ. (2023). Consumers Care About Sustainability—and Back it up with their Wallets. Retrieved from https://nielseniq.com/global/en/insights/report/2023/consumers-care-about-sustainability-and-back-it-up-with-their-wallets/

103 BCG (2022). Consumers are the Key to Taking Green Mainstream. Retrieved from https://www.bcg.com/publications/2022/consumers-are-the-key-to-taking-sustainable-products-mainstream

104 Adams, C. et al. (2024). State of the Consumer 2024: What's Now and What's Next. Retrieved from https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/state-of-consumer#/

105 Adams, C. et al. (2024). State of the Consumer 2024: What's Now and What's Next. Retrieved from https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/state-of-consumer#/

106 Bocken, N.M.P. et al. (2014). A Literature and Practice Review to Develop Sustainable Business Model Archetypes. Journal of Cleaner Production, Vol. 65, pp. 42-56.

References

107 Szekely, F., Strebel, H. (2013). Incremental, Radical and Game-Changing: Strategic Innovation for Sustainability. Corporate Governance, Vol. 13, Issue 5, pp. 467-481.

108 Statista (2024). Industries & Markets: Industry 4.0: In-Depth Market Analysis. Retrieved from https://www.statista.com/study/66974/in-depth-report-industry-40/

109 Statista (2024). Number of Internet of Things (IoT) Connections Worldwide from 2022 to 2023, with Forecasts from 2024 to 2033 (2024). Retrieved from https://www.statista.com/statistics/1409852/global-cleantech-market-size-country-region/

110 Bertoni, M., Bertoni, A. (2022). Designing Solutions with the Product-Service Systems Digital Twin: What is Now and What is Next? Computers in Industry, Vol. 138, p. 103629.

111 Hart, S.L., Milstein, M.B. (2003). Creating Sustainable Value. Academy of Management Perspectives, Vol. 17, Issue 2, pp. 56-67.

112 Kohtamäki, M. et al. (2018). Alliance Capabilities: A Systematic Review and Future Research Directions. Industrial Marketing Management, Vol. 68, pp. 188-201.

113 Mordor Intelligence (2024). Digital Transformation Market Size (2024-2029). Retrieved from https://www.mordorintelligence.com/industry-reports/digital-transformation-market/market-size

114 Davidson, N.C. et al. (2018). Global Extent and Distribution of Wetlands: Trends and Issues. Marine and Freshwater Research, Vol. 69, Issue 4, pp. 620-627.

115 Statista (2024). Market Size for Key Clean Energy Technologies Worldwide in Selected Countries and Regions in 2030. Retrieved from https://www.statista.com/statistics/1409852/global-cleantech-market-size-country-region/

116 Accenture (2021). The Critical Role of Virtual Twins in Accelerating Sustainability. Retrieved from https://www.accenture.com/us-en/blogs/industry-digitization/accelerating-sustainability-with-virtual-twins

117 Tsamados, A. et al. (2024). Human Control of AI Systems: From Supervision to Leaming. AI and Ethics.

118 Daugherty, P.R., Wilson, H.J. (2018). Human + Machine: Reimagining Work in the Age of AI. Harvard Business Press.

119 IBM (2024). Cost of a Data Breach Report 2024. Retrieved from https://www.ibm.com/reports/data-breach

120 Gartner (2023). Top Strategic Technology Trends. Retrieved from https://emt.gartnerweb.com/ngw/globalassets/en/publications/documents/2023-gartner-top-strategic-technology-trends-ebook.pdf

121 Reuters (2024). US Electric Utilities Brace for Surge in Power Demand from Data Centres. Retrieved from https://www.reuters.com/business/energy/us-electric-utilities-brace-surge-power-demand-data-centers-2024-04-10/

122 Forbes (2024). AI Power Consumption: Rapidly Becoming Mission-Critical. Retrieved from https://www.forbes.com/sites/bethkindig/2024/06/20/ai-power-consumption-rapidly-becoming-mission-critical/

123 Kohtamäki, M. et al. (2018). Alliance Capabilities: A Systematic Review and Future Research Directions. Industrial Marketing Management, Vol. 68, pp. 188-201.

124 Alves, J. (2023). Is Industry 5.0 a human-centred approach? A Systematic Review. Processes, Vol. 11, Issue 1, p. 193.

125 European Commission (2023). EU AI Act: First Regulation on Artificial Intelligence. Retrieved from https://www.europarl.europa.eu/topics/en/article/20230601STO93804/eu-ai-act-first-regulation-on-artificial-intelligence

126 Reuters (2024). US, Britain, EU to Sign First International AI Treaty. Retrieved from https://www.reuters.com/technology/artificial-intelligence/us-britain-eu-sign-agreement-ai-standards-ft-reports-2024-09-05/

127 United Nations (2015). United Nations Framework Convention on Climate Change: Paris Agreement (Article 4, paragraph 2). Retrieved from https://unfccc.int/sites/default/files/english_paris_agreement.pdf

128 United Nations (2015). United Nations Framework Convention on Climate Change: Paris Agreement (Article 4, paragraph 2). Retrieved from https://unfccc.int/sites/default/files/english_paris_agreement.pdf

129 Convention on Biological Diversity (2022). The Post-2020 Global Biodiversity Framework. Retrieved from https://www.cbd.int/doc/c/409e/19ae/369752b245f05e88f760aeb3/wg2020-05-l-02-en.pdf

130 European Commission (2024). EU Emissions Trading System. Retrieved from https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

131 Bellora, C., Fontagné, L. (2023). EU in Search of a Carbon Border Adjustment Mechanism. Energy Economics, Vol. 123, p. 106673.

132 Hummel, K., Jobst, D. (2024). An Overview of Corporate Sustainability Reporting Legislation in the European Union. Accounting in Europe, pp. 1-36.

133 U.S. Congress (2022). Inflation Reduction Act of 2022 (Public Law No: 117-169). Retrieved from https://www.congress.gov/bill/117th-congress/house-bill/5376/text

134 Central Committee of the Communist Party of China. (2021). The 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China (2021-2025). Retrieved from https://cset.georgetown.edu/wp-content/uploads/t0284_14th_Five_Year_Plan_EN.pdf

135 Kim, G. (2023). Japan's Carbon Neutrality and Green Growth Strategy. KIEP Research Paper, World Economy Brief, pp. 23-08.

136 Government of Japan. (2021). Japan's Green Growth Strategy Will Accelerate Innovation. Retrieved from https://www.japan.go.jp/kizuna/2021/09/green_growth_strategy.html

137 European Commission. The European Chips Act. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en

138 Digital Operational Resilience Act (DORA). European Insurance and Occupational Pensions Authority. Retrieved from https://www.eiopa.europa.eu/digital-operational-resilience-act-dora_en

139 International Panel on Climate Change (2023). Sixth Assessment Report. Retrieved from https://www.ipcc.ch/report/sixth-assessment-report-cycle/

140 UNEP (2023). Emissions Gap Report. Retrieved from https://www.unep.org/resources/emissions-gap-report-2023

141 IPCC (2023). AR6 Climate Change 2023: Synthesis Report. pp. 35-115. Retrieved from https://www.ipcc.ch/report/ar6/syr/

142 Ritchie, H. (2020). Sector by Sector: Where do global Greenhouse Gas Emissions Come From?" Retrieved from: https://ourworldindata.org/ghg-emissions-by-sector

143 Ritchie, H. (2020). Sector by Sector: Where do global Greenhouse Gas Emissions Come From?" Retrieved from: https://ourworldindata.org/ghg-emissions-by-sector

144 United Nations Climate Change (2016). The Paris Agreement. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement

145 WEF (2024). Global Risks Report 2024. Retrieved from https://www.weforum.org/publications/global-risks-report-2024/

146 WEF (2024). Global Risks Report 2024. Retrieved from https://www.weforum.org/publications/global-risks-report-2024/

147 Global System Institute (2023). Global Tipping Points Summary Report. Retrieved from https://global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/1-3-2-current-state-of-knowledge-on-tipping-points-in-the-biosphere/

148 Global System Institute (2023). Global Tipping Points Summary Report. Retrieved from https://global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/1-3-2-current-state-of-knowledge-on-tipping-points-in-the-biosphere/1-3-2-1-tropical-forests/

149 Global System Institute (2023). Global Tipping Points Summary Report. Retrieved from https://global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/1-3-2-current-state-of-knowledge-on-tipping-points-in-the-biosphere/1-3-2-2-boreal-forests-tundra/

150 Global System Institute (2023). Global Tipping Points Summary Report. Retrieved from https://global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/1-3-2-current-state-of-knowledge-on-tipping-points-in-the-biosphere/1-3-2-3-temperate-forests/

151 Global System Institute (2023). Global Tipping Points Summary Report. Retrieved from https://global-tipping-points.org/section1/1-earth-system-tipping-points/1-3-tipping-points-in-the-biosphere/1-3-2-current-state-of-knowledge-on-tipping-points-in-the-biosphere/1-3-2-4-savannas-grasslands/

152 Earth Overshoot Day (2024). Country Overshoot Day. Retrieved from https://overshoot.footprintnetwork.org/newsroom/country-overshoot-days/

153 Earth Overshoot Day (2024). Country Overshoot Day. Retrieved from https://overshoot.footprintnetwork.org/newsroom/country-overshoot-days/)

154 UNEP (2024). Global Resource Outlook. Retrieved from https://www.unep.org/resources/Global-Resource-Outlook-2024

155 UNEP (2024) Global Resource Outlook. Retrieved from https://www.unep.org/resources/Global-Resource-Outlook-2024

156 UNEP (2024). Global Waste Management Outlook. Retrieved from https://www.unep.org/resources/global-waste-management-outlook-2024

157 UNEP (2024). Global Waste Management Outlook. Retrieved from https://www.unep.org/resources/global-waste-management-outlook-2024

158 e-Waste Monitor (2024). Global e-Waste Monitor 2024. Retrieved from https://ewastemonitor.info/wp-content/uploads/2024/03/GEM_2024_18-03_web_page_per_page_web.pdf

159 e-Waste Monitor (2024). Global e-Waste Monitor 2024. Retrieved from https://ewastemonitor.info/wp-content/uploads/2024/03/GEM_2024_18-03_web_page_per_page_web.pdf

160 WEF (2023). We're on the Brink of a 'Polycrisis' – How Worried Should We Be? Retrieved from: https://www.weforum.org/agenda/2023/01/polycrisis-global-risks-report-cost-of-living/

161 WEF (2023). We're on the Brink of a 'Polycrisis' – How Worried Should We Be? Retrieved from: https://www.weforum.org/agenda/2023/01/polycrisis-global-risks-report-cost-of-living/

162 WEF (2023). Global Risks Report 2023. Retrieved from: https://www3.weforum.org/docs/WEF_Global_Risks_Report_2023.pdf

References

163 EY (2022). The CEO Imperative: How to Remain Resolute on Investment as Inflation Surges. Retrieved from: https://assets.ey.com/content/dam/ey-sites/ey-com/en_gl/topics/consulting/ey-ceo-outlook-pulse-survey-october-2022-global-report.pdf

164 IBM (2024). IBM X-Force: Threat Intelligence Index 2024. Retrieved from https://www.ibm.com/downloads/cas/L0GKXDWJ

165 Chari et al. (2024). Resilience Compass Navigation through Manufacturing Organization Uncertainty – a Dynamic Capabilities Approach using Mixed Methods.

166 Agrawal, N., Jain, R.K. (2022). Insights from Systematic Literature Review of Supply Chain Resilience and Disruption. Benchmarking: An International Journal, Vol. 29, Issue 8, pp. 2495-2526.

167 European Commission (2024). Manufacturing as a Service: Technologies for Customised, Flexible, and Decentralised Production on Demand. Retrieved from: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl4-2024-twin-transition-01-03

168 Beach, R. (2000). A Review of Manufacturing Flexibility. European Journal of Operational Research, Vo. 122, Issue 1, pp. 41-57.

169 Zhang, Q. et al. (2003). Manufacturing Flexibility: Defining and Analyzing Relationships among Competence, Capability, and Customer Satisfaction. Journal of Operations Management, Vol. 21, Issue 2, pp. 173-191.

170 De Toni, A., Tonchia, S. (1998). Manufacturing Flexibility: A Literature Review. International Journal of Production Research, Vol. 36, Issue 6, pp. 1587-1617.

171 New York Fed (2022). The GSCPI: A New Barometer of Global Supply Chain Pressures. Retrieved from https://www.newyorkfed.org/medialibrary/media/research/staff_reports/sr1017.pdf

172 Milzam, M. et al. (2020). Corona Virus Pandemic Impact on Sales Revenue of Micro Small and Medium Enterprises (MSMEs) in Pekalongan City, Indonesia. Journal of Vocational Studies on Applied Research, Vol. 2, Issue 1, pp 7-10.

173 Dittfeld, H. et al. (2022). The Effect of Production System Characteristics on Resilience Capabilities: A Multiple Case Study. International Journal of Operations and Production Management, Vol. 42, Issue 13, pp. 103-127.

174 Time (2023). The Ultimate Election Year: All the Elections Around the World in 2024. Time. Retrieved from https://time.com/6550920/world-elections-2024/

175 Gartner (2024). Hype Cycle for Manufacturing Operations Strategy. Retrieved from https://www.gartner.com/en/documents/5593859

176 Hsu, C.-H. et al. (2022). Enhancing Supply Chain Agility with Industry 4.0 Enablers to Mitigate Ripple Effects Based on Integrated QFD-MCDM: An Empirical Study of New Energy Materials Manufacturers. Mathematics, Vol. 10, Issue 10, p. 1635.

177 Ghobakhloo, M., et al. (2023). Industry 5.0 Implications for Inclusive Sustainable Manufacturing: An Evidence-Knowledge-Based Strategic Roadmap. Journal of Cleaner Production, Vol. 417, p. 138023.

178 Driedonks, B. et al. (2024). How to Navigate Pricing During Disinflationary Times. Retrieved from https://www.mckinsey.com/capabilities/growth-marketing-and-sales/our-insights/how-to-navigate-pricing-during-disinflationary-times#/

179 Driedonks, B. et al. (2024). How to Navigate Pricing During Disinflationary Times. Retrieved from https://www.mckinsey.com/capabilities/growth-marketing-and-sales/our-insights/how-to-navigate-pricing-during-disinflationary-times#/

180 Mckinsey & Company (2024). Help Wanted: Charting the Challenge of Tight Labor Markets in Advanced Economies. Retrieved from https://www.mckinsey.com/mgi/our-research/help-wanted-charting-the-challenge-of-tight-labor-markets-in-advanced-economies

181 Mckinsey & Company (2024). Help Wanted: Charting the Challenge of Tight Labor Markets in Advanced Economies. Retrieved from https://www.mckinsey.com/mgi/our-research/help-wanted-charting-the-challenge-of-tight-labor-markets-in-advanced-economies

182 Deloitte (2023). 2024 Manufacturing Industry Outlook. Retrieved from https://www2.deloitte.com/us/en/insights/industry/manufacturing/manufacturing-industry-outlook.html

183 Baldwin and Ito (2022). The Smile Curve: Evolving Sources of Value Added in Manufacturing. Canadian Journal of Economics, Vol. 54, Issue 4, pp. 1842-1880.

184 World Bank (2024). Shared Prosperity: Monitoring Inclusive Growth. Retrieved from https://www.worldbank.org/en/topic/poverty/brief/global-database-of-shared-prosperity

185 ILO (2022). Global Estimates of Modern Slavery: Forced Labour and Forced Marriage Report. Retrieved from https://www.ilo.org/publications/major-publications/global-estimates-modern-slavery-forced-labour-and-forced-marriage

186 National Association of Manufacturers (2019). New Report Dives Into Retaining The Aging Manufacturing Workforce. Retrieved from https://nam.org/new-report-dives-into-retaining-the-aging-manufacturing-workforce-5579/?stream=workforce

187 National Association of Manufacturers (2023).Manufacturers' Outlook Survey: Second Quarter 2023. Retrieved from https://nam.org/2023-second-quarter-manufacturers-outlook-survey/

188 Make UK (2024). A Millennial Problem for Manufacturers. Retrieved from https://www.makeuk.org/insights/blogs/a-millennial-problem-for-manufacturers#:~:text=Attracting%20and%20retaining%20a%20younger,the%20problem%20could%20be%20generational.

189 Parasable (2024). Gen Z Warms to Manufacturing Jobs, But Misperceptions Persist. Retrieved from https//parsable.com/blog/future-of-work/gen-z-warms-to-manufacturing-jobs-but-misperceptions-persist/

190 IBM (2024). What is Environmental, Social and Governance (ESG)? Retrieved from https://www.ibm.com/topics/environmental-social-and-governance

191 Grand View Research (2023). ESG Investing Market Size & Trends. Report. Retrieved from https://www.grandviewresearch.com/industry-analysis/esg-investing-market-report

192 Bokrantz, J. et al. (2020). Smart Maintenance: An Empirically Grounded Conceptualization. International Journal of Production Economics, Vol. 223, p. 107534.

193 ILO (2018). The Benefits of Gender Balance. Retrieved from https://webapps.ilo.org/infostories/en-GB/Stories/Employment/beyond-the-glass-ceiling#benefits

194 Chavez, C.A. (2023). Sustainability-as-a-Service: Advancing Digital Servitization for Industrial Sustainability. PhD Thesis. Retrieved from https://research.chalmers.se/publication/538429/file/538429_Fulltext.pdf

195 Harris, K. et al. (2018). Labor 2030: The Collision of Demographics, Automation and Inequality. Retrieved from https://www.bain.com/insights/labor-2030-the-collision-of-demographics-automation-and-inequality/

196 Deloitte and The Manufacturing Institute DEI Study (2021). Beyond Reskilling, Manufacturing's Future Depends on Diversity, Equity, and Inclusion. Retrieved from https://themanufacturinginstitute.org/research/beyond-reskilling-manufacturings-future-depends-on-diversity-equity-and-inclusion/

197 BCG (2018). How Diverse Leadership Teams Boost Innovation. Retrieved from https://www.bcg.com/publications/2018/how-diverse-leadership-teams-boost-innovation

198 European Commission (2021). Industry 5.0: Towards a Sustainable, Human-centric and Resilient European Industry. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/

199 PwC (2023). Winning Today's Race while Running Tomorrow's. Retrieved from https://www.pwc.com/gx/en/ceo-survey/2023/main/download/26th_CEO_Survey_PDF_v1.pdf

200 Reuters (2024). US, Britain, EU to Sign First International AI Treaty. Retrieved from https://www.reuters.com/technology/artificial-intelligence/us-britain-eu-sign-agreement-ai-standards-ft-reports-2024-09-05/

201 GMK (2022). Carbon Tax will Cost for European Steel Importers €2 Billion/Year – BCG. Retrieved from https://gmk.center/en/news/carbon-tax-will-cost-for-european-steel-importers-e2-billion-year-bcg/

202 Kannan, D. et al. (2023). Smart Manufacturing as a Strategic Tool to Mitigate Sustainable Manufacturing Challenges: A Case Approach. Annals of Operations Research, Vol. 331, Issue 1, pp. 543-579.

203 Liu, W. et al. (2023). How Renewable Energy Investment, Environmental Regulations, and Financial Development Derive Renewable Energy Transition: Evidence from G7 Countries. Renewable Energy, Vol. 206, pp. 1188-1197.

204 European Commission. (2020). A New Industrial Strategy for Europe. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0102

205 European Commission (2021). Industry 5.0: Towards a Sustainable, Human-centric and Resilient European Industry. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/

206 European Commission (2019). The European Green Deal. Retrieved from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

207 European Commission (2020). Circular Economy Action Plan: for a Cleaner and more Competitive Europe. Retrieved from https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en

208 European Commission (2020). Critical Raw Materials Resilience: Charting a Path Towards Greater Security and Sustainability. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0474

209 Machado, C.G. et al. (2020). Sustainable Manufacturing in Industry 4.0: An Emerging Research Agenda. International Journal of Production Research, Vol. 58, Issue 5, pp. 1462-1484.

210 Badhoutiya, A. et al. (2023). Regenerative Manufacturing: Crafting a Sustainable Future through Design and Production. E3S Web of Conferences, Vol. 453, p. 01038.

211 Despeisse, M. (2023). Applying Regenerative Sustainability Principles in Manufacturing. Eco-Design for Sustainable Products, Services and Social Systems, Vol. I, pp. 133-145.

212 Ellen MacArthur Foundation (2019). Circular Economy System Diagram. Retrieved from https://www.ellenmacarthurfoundation.org/circular-economy-diagram

213 Hahn, T., Tampe, M. (2021). Strategies for Regenerative Business. Strategic Organization, Vol. 19, Issue 3, pp. 456-477

The World Manufacturing Foundation

Vision

"We strive to enhance manufacturing's role as a dynamic and positive driver for economic, social, and environmental growth and sustainability".

Mission

The World Manufacturing Foundation is an open platform spreading industrial culture worldwide. We promote innovation and development in the manufacturing sector, with the fundamental goal of improving societal wellbeing and inclusive growth in all nations through dialogue and cooperation among the manufacturing sector's key players.

We will pursue our goals by:

- supporting and shaping local and international industrial agendas
- providing a framework through which companies, governments, academic institutions and social organisations can interact or collaborate, acting as a catalyst for finding innovative solutions to major global challenges
- creating and disseminating knowledge in both policy and technology through local and international meetings and publications.

Spreading Industrial Culture Worldwide

The World Manufacturing Foundation was formally established in May 2018 in Milan, Italy, as a platform to promote industrial culture and sustainable manufacturing practices worldwide. This undertaking was spearheaded by three founding partners: Confindustria Lombardia, IMS International, and Politecnico di Milano. The Foundation aims to spread industrial culture by expanding knowledge, promoting innovation, and fostering cooperation in the manufacturing sector.

The Foundation capitalises on its wealth of experience in hosting annual manufacturing events to discuss the most pressing challenges confronting the sector. In fact, long before the Foundation was formally established, the annual World Manufacturing Forum has been staged since 2011. The very first edition was held in Cernobbio in Lombardy and started as an important platform for global industry leaders and other stakeholders to exchange opinions on different issues related to manufacturing. The Forum started as a project funded by the European Commission, which has also supported its succeeding editions.

The World Manufacturing Foundation also has the support of important organisations. The Foundation was kick-started with the support of Regione Lombardia, which has also provided financial support in the last few years. In 2018, the World Manufacturing Foundation also signed a joint declaration with the United Nations Industrial Development Organization (UNIDO) to promote a common global agenda on technological innovation and inclusive and sustainable industrialisation, and to advance the 2030 Agenda for Sustainable Development.

The business model which defines the Foundation is that of the Triple Helix. Its competitiveness is empowered through an intersectoral collaboration engaging industry, academia, and government. This is evident in the nature of its founding and key partners and a large community of institutional partners from all over the world, which support the Foundation's initiatives.

World Manufacturing Foundation Members

CONFINDUSTRIA Lombardia

POLITECNICO MILANO 1863

Thanks to

European Commission

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Regione Lombardia

2024 KEY RECOMMENDATIONS BY THE WORLD MANUFACTURING FOUNDATION

1. EMBRACE CHANGE TO OVERCOME CRITICAL MANUFACTURING CHALLENGES IN A VUCA WORLD
2. LEVERAGE BUSINESS INTELLIGENCE & DATA ANALYTICS TO NAVIGATE THE GRAND MANUFACTURING CHALLENGES AND OPPORTUNITIES
3. FOSTER INNOVATION AT THE HEART OF MANUFACTURING TRANSFORMATION
4. PLAN STRATEGICALLY DESPITE THE PACE OF DAY-TO-DAY MANUFACTURING BUSINESS OPERATIONS
5. IMPLEMENT ROBUST RISK MANAGEMENT PRACTICES TO IDENTIFY POTENTIAL THREATS AND DEVELOP CONTINGENCY PLANS
6. IDENTIFY AND ADOPT BEST MANUFACTURING PRACTICES TO COVER THE BASICS OF COMPETITIVENESS
7. APPRECIATE SUSTAINABILITY AS A MANUFACTURING BUSINESS OPPORTUNITY RATHER THAN PREDOMINANTLY A CHALLENGE
8. EXPLORE NEW MANUFACTURING TECHNOLOGIES THAT CAN SUPPORT THE DIGITAL-GREEN TRANSITION
9. INVEST IN BUILDING A TALENT PIPELINE & DEVELOPING FUTURE LEADERS FOR A STRONG MANUFACTURING SECTOR
10. BUILD STRATEGIC PARTNERSHIPS TOWARDS A COOPETITIVE MANUFACTURING BUSINESS ECOSYSTEM

WORLD MANUFACTURING FOUNDATION

World Manufacturing Foundation
Global Headquarters:
Via Pantano, 9 - 20122 Milano, Italy

worldmanufacturing.org