TRENDS REPORT

The Future Of Manufacturing

Disruptive Innovations In Manufacturing Will Reshape Entire Industries

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Summary

Manufacturers must become quicker, smarter, and greener to survive in a fast-changing world. This report describes the four big trends affecting the manufacturing industry — and the eight technology clusters that form the toolkit that technology executives will use to respond in the short, medium, and long term.

Four Big Trends Shape The Future Of Manufacturing

In volatile market conditions, manufacturers must become quicker, smarter, and greener to survive. The transformation of traditional — often conservative — manufacturing firms must involve more than just making existing physical processes more efficient. Business and technology leaders must work together to build future fit organizations that are adaptive, creative, and resilient, unlocking more sustainable and profitable customer relationships as a result. In crafting their response to the four key trends already reshaping manufacturing, executives are trying to steer the optimal course between old and new, cautious and bold, or physical and digital (see Figure 1). They are:

- **Integrating digital technologies with physical products, combining grease with code.** Even the most traditional industrial players are rushing to acquire and embed digital capabilities. But the physical products, and the hard-won industrial skills that create them, don't go away. A rich digital experience doesn't replace a well-built car or a dependable and resilient piece of industrial machinery. Rather, digital augments the product and enables manufacturers to design, build, sell, use, reuse, support, and value it in new ways. Physical products endure, but the companies that build them must make the shift from grease to code to survive.
- **Adapting to a changing world order with local, near, and far manufacturing capacity.** Rumors of globalization's demise are premature, but geopolitical tensions, a global pandemic, economic pressures, an aging workforce, and technological advances combine to alter the balance in a decades-old model: It's no longer wise to assume everything will be made in China — or anywhere else. Smart leaders are moving away from long and brittle supply chains to embrace more flexible and resilient supply networks. These combine the cost benefits of offshore manufacturing with the speed-to-market and political benefits of moving jobs closer to customers, creating an overall proposition that's neither "just in time" nor "just in case" but just right. 3D printing, hardware and software automation, and the microfactory approach that firms like electric mobility company Arrival or software and robotics company Bright Machines promote all help make local manufacturing part of the strategy.
- **Electrifying, decarbonizing, and then manufacturing sustainably.** According to Eurostat, manufacturing and construction (34%), electricity supply (19%), and transport services (8%) were responsible for more than 60% of greenhouse gas emissions in the European Union (EU) in Q2 2021. But few would seriously argue

that manufacturing, power generation, or the movement of goods can simply stop. Electrification of key industrial processes has been underway for years, and projects to decarbonize steel production or trap excess carbon inside construction materials show some promise. But most firms are just getting started on serious programs to manufacture more sustainably. This will require them to make decisions about the source, nature, and use of energy and raw materials, while cutting waste, improving efficiency, and reevaluating the role of recycling in the manufacture, use, and eventual disposal of finished goods.

- **Balancing the automation triangle to get the best from hardware, software, and people.** The automation of both hardware (robots, collaborative robots [cobots], drones, autonomous vehicles, etc.) and software (AI and machine learning) has transformed manufacturing, manufacturers, and their workforce. Although human workers' roles have sometimes altered beyond recognition, they remain critically important: Few industrial workflows will suit entirely automated, lights-out operation any time soon. Forrester's automation triangle describes the need to balance hardware, software, and humans to achieve desired business outcomes, ensuring that each mostly works on the tasks to which they bring greatest value. Far from replacing human workers, well-deployed hardware and software automation augment them, extend their reach, and take up some of the slack in today's challenging labor market.

Figure 1

Four Big Trends Shape The Future Of Manufacturing

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Eight Key Technology Clusters Power The Future Of Manufacturing

Digital technologies play a pivotal role in the transformation of manufacturing: Industry conversations around smart manufacturing, the industrial internet, and Industry 4.0 (or even 5.0 for some) mostly focus on the contribution of new hardware and software. We previously discussed 20 technologies powering manufacturing's digital transformation, and that report barely scratched the surface of the many technologies in play here.

Technology leaders must prepare to address the impact of eight overlapping technology clusters on their business, their employees, their partners, and their customers (see Figure 2). These technology clusters cover:

- **Transporting, storing, and processing data.** Industrial data must be securely collected, stored, and transported, both inside the factory and beyond its walls. Although technology leaders in the manufacturing sector have been slower to adopt cloud than their peers in other industries, cloud computing is part of most conversations with our manufacturing clients today. Edge computing, cloud computing, and the IT and operational technology (OT) networks that connect them are enabling capabilities for any digital project in the manufacturing sector.
- **Controlling industrial workflows.** Software controls key industrial processes and has done so for decades. Supervisory control and data acquisition systems literally keep the lights on, delivering real-time control of critical infrastructure in manufacturing, the energy sector, and beyond. Product lifecycle management tools track products from ideation to creation, while a manufacturing execution system tracks physical items as they move through the factory from raw material to finished product. Enterprise resource planning or digital operations platform solutions record transactions across the business. All these tools play interconnected and overlapping roles in keeping the machinery of manufacturing running smoothly, and there are clear opportunities to remove duplication, harmonize data models, enhance interoperability, and support safe and secure remote operations.
- **Securing the integrated reporting of progress against plan.** In both process and discrete manufacturing, various stakeholders need to be aware of progress in complex workflows. Down on the factory floor, up in the control room, or across the planet at head office, flashing Andon lights, large display screens, machine-specific industrial human/machine interface (HMI) panels, and employees' tablets, smartphones, and wearables play their part in conveying information about stock levels, finished goods, and deviation from expectations. Shared visibility into and accountability for what's happening now and what happened in the past is often the first step to deriving the insights to support improving in the future.
- **Using software automation to derive insights and recommend or take action.** Historical data, timely observations from IoT sensors and other systems, and knowledge of future states — both internal (e.g., production capacity, maintenance schedules) and external (e.g., supply chain flexibility, customer demand, the weather) — combine to offer manufacturers more granular control over their business. Machine learning and AI build models of optimal operations (often in the cloud) and then monitor tens, hundreds, or even thousands of variables at the

edge to quickly alert human operators when things are likely to stray off course. In some situations, software may be authorized to make corrections without waiting for explicit permission from a watching human.

- **Understanding the impact of materials production.** Manufacturers are in the business of making things. The machines they use to do this — the metal presses, the milling machines, the lathes, the 3D printers, and all the rest — aren't directly the responsibility of technology executives or the focus of this report. But those machines no longer exist in an operational technology bubble, completely divorced from an organization's digital strategy. A technology executive is unlikely to choose between one lathe and another, but they absolutely should expect to understand the impact of those machines — the data they generate and the data they consume — on other systems, processes, and workflows. The growth in remote or autonomous operation also directly touches technology executives' sphere of interest and influence.
- **Sensing the environment.** Industrial IoT sensors measure and observe machines, people, raw materials, finished goods, and entire workflows, providing much of the data that feeds the other technology clusters considered here. From the simple measurement of temperature, humidity, or vibration to more complex computer vision use cases around quality control or worker safety, the falling cost of sensors, connectivity, storage, and compute means that we can observe industrial environments more than ever before. In markets like the EU, privacy and data protection legislation tightly constrains the observation of individual workers.
- **Using hardware automation to do the heavy lifting.** We've come a long way since General Motors installed the Unimate industrial robot on a New Jersey production line back in 1961. Today, few major manufacturing lines could operate without their rows of caged industrial robots. Hardware automation is also gaining traction in less structured workflows as well as those that require closer interaction with humans. Cobots, drones, autonomous mobile robots (AMRs), and automated guided vehicles are among the hardware automation solutions playing their part in picking, assembling, carrying, packing, or inspecting parts and finished products.
- **Ensuring worker safety.** Manufacturing is a dangerous business, and keeping workers safe should be managers' overriding concern. There's a worker safety element to each technology cluster, but there's also value in drawing them together in their own right here. Robots lift the heaviest loads, IoT sensors monitor the buildup of noxious gases, and computer vision cameras watch for humans moving in front of AMRs, lowering the risk of injury in the workplace. These technologies also support the more thoughtful deployment of finite human resources, improving the employee experience and retention by ensuring that the

current labor shortage leads to smarter use of the available workforce.

Figure 2

Eight Key Technology Clusters Power The Future Of Manufacturing

Enabled by: / Enabler of:	Data storage and compute	Industrial workflows	Reporting progress	Insights and action	Materials production	Sensors	Hardware automation	Worker safety
Data storage and compute	●	●	●	●	●	●	●	●
Industrial workflows		●			●		●	
Reporting progress		●	●	●	●		●	
Insights and action		●	●	●	●		●	●
Materials production					●			
Sensors		●	●	●	●	●	●	●
Hardware automation		●			●		●	●
Worker safety		●	●	●	●			●

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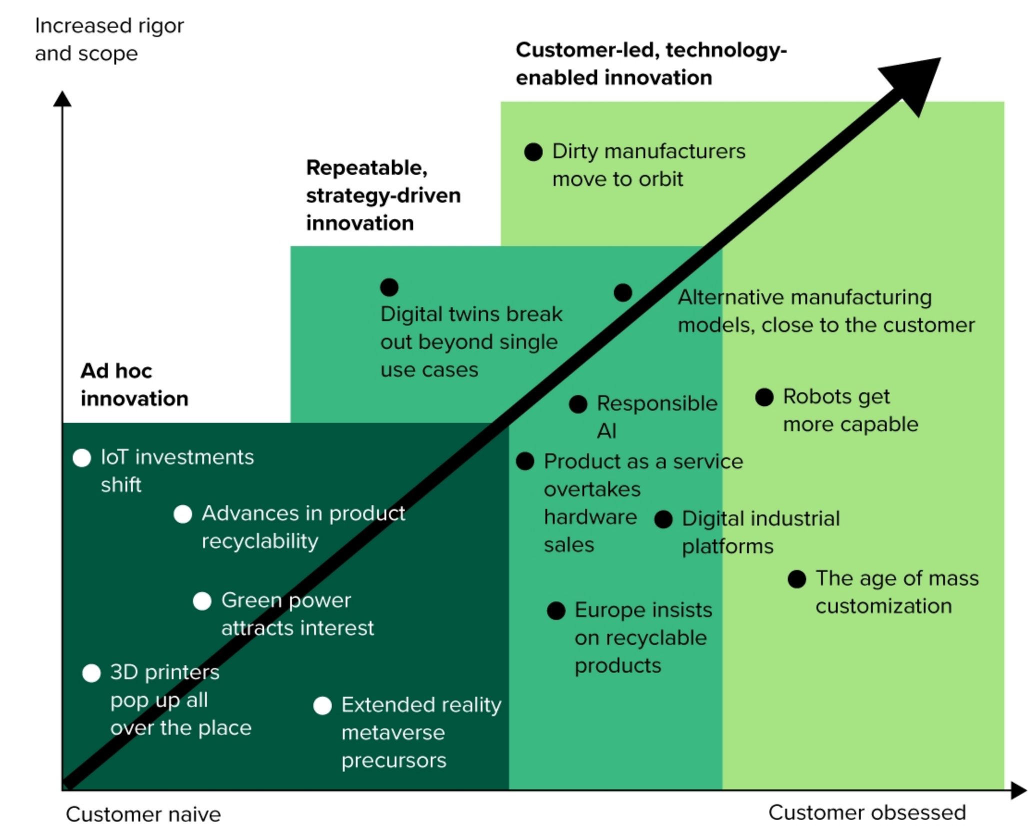
Three Innovation Horizons Define The Future Of Manufacturing

Manufacturers draw on specific technologies in eight broad technology clusters to tackle the four big trends shaping their sector. But they won't implement all the changes — or feel all the external pressures — at once. Manufacturers will deploy ad hoc innovations as isolated instances that tinker around the edges of existing processes and workflows over the next year or two. Learning lessons from those ad hoc innovations, aligning them to corporate strategy, and making them repeatable at scale will often require five to 10 years. The really big shifts to demolish organizational silos and deliver customer-led transformation of the industry will play out over a decade or more (see Figure 3).

Figure 3

Three Innovation Horizons Define The Future Of Manufacturing



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Innovation In The Short Term Is Mostly Ad Hoc

In the short term (i.e., the next year or two), manufacturers will see:

- **3D printers starting to pop up all over the place.** 3D printing (or additive manufacturing) plays a role in everything from product prototyping to volume production of finished parts; it supports the optimization of supply networks and underpins new business models. Printers produce plastics, metals, advanced composite materials, and more. While printers are becoming an increasingly familiar sight in manufacturing settings, most are still deployed alongside existing equipment and kept separate from broader processes and workflows. These point solutions are affordable enough to try and good enough to deliver value. The broader rethinking of manufacturing workflows to make the best use of additive manufacturing's full potential is only just beginning.

- **Advances appearing in product recyclability.** Manufacturers are aware that they need to improve the sustainability of their products and operations. Enthusiasm for the circular economy misses the fact that, today, the circle keeps breaking and few of the initiatives are economic at scale. But the direction of travel is clear. Siemens' new recyclable wind turbine blades are being installed in the North Sea during 2022, and competitors have similar aspirations to increase blade recyclability. BMW Group manufactures vehicles using almost 30% recycled and reused material on average: The company's i Vision Circular concept foresees cars made from 100% recycled materials that are themselves 100% recyclable. Renault's Refactory is "entirely dedicated to the circular economy." It will take time, money, and partnerships to design products that can be disassembled easily and then build the distribution and processing networks to collect, separate, transport, and repurpose the component parts.
- **IoT investments shifting as manufacturers scramble to reduce energy bills.** The cost of energy continues to rise: The benchmark for Europe is Germany, where next year's energy traded at more than €380 per megawatt-hour in July 2022, more than six times the price a year ago. Reducing their energy bill has never been more important for manufacturers. They're repurposing existing investments in IoT to deliver actionable data on the connection between energy and production, supporting strategic initiatives to cut waste and boost useful output per kilowatt consumed. Bosch factories around the world have been carbon neutral since 2020, and the company's AI and IoT solutions were pivotal in achieving that objective. As energy bills grow, plenty of others will be looking to see what they can learn from early adopters like Bosch.
- **Green power and carbon capture attracting interest.** Orbital Marine's O2 turbine generates 2 megawatts of electricity off the coast of Scotland. Unlike other offshore turbines, this one harnesses the reliable movement of water rather than less predictable wind. The Orca carbon capture and storage (CCS) facility can pull 4,000 tons of CO_2 from the air every year; it then uses clean Icelandic renewable energy to trap it in volcanic rock. Hybrit tapped Swedish hydroelectric power and green hydrogen to produce the carbon-free steel used in a Volvo truck. In the UK, Zero Carbon Humber is exploring the feasibility of combining bioenergy, CCS, and

hydrogen to turn the UK's most carbon-intensive industrial cluster into one that's eventually carbon negative. The numbers here are tiny, and none of these projects will make a difference without cutting costs and scaling dramatically. Many projects will fail, but we will all learn from their experience.

- **Extended reality solutions becoming the precursors to the industrial metaverse.** Plant Lydia in Shenyang, China, is the first BMW plant to be modeled virtually from initial design to construction and ongoing operation. Volvo uses Varjo's mixed-reality headset to monitor test drivers' interaction with features for future cars while they drive real cars on real roads. Engineers at Kawasaki Heavy Industries use Microsoft HoloLens to collaborate remotely using digital twins of the industrial robots they manufacture and maintain. Siemens has a track record of building digital twins with physical fidelity, while Nvidia is better known for the visual fidelity of its twins; the two recently partnered to combine their strengths. Many of these firms make bold claims that their existing technology delivers an industrial metaverse, although the reality is less dramatic: These may be precursors to the industrial metaverse, but it is still a long way off.

Innovation In The Medium To Long Term Will Be Repeatable And Strategy Driven

In the medium to long term (i.e., the next five to 10 years), today's innovation projects will move out of the R&D lab and begin to scale. We expect to see:

- **Global tensions driving alternative manufacturing models close to the customer.** Supply chain responses to geopolitical tensions and the pandemic in the years around 2020 were surprisingly rapid and effective but unsustainably expensive and inefficient. Despite the headlines, most goods kept moving, but only because firms threw money at quickly reprioritizing, retasking, and reworking existing assets. In the medium to long term, manufacturers and their supply chain partners will adopt a more strategic approach, shifting from long, brittle supply chains to resilient supply networks. They will deploy more automation and even microfactories to create some cost-effective local production, even in the most expensive markets. But shifting manufacturing capacity takes time: Intel's new semiconductor plant in Magdeburg, Germany, will take at least five years to progress from announcement to operation.
- **Europe insisting on recyclable products and much of the world following.** Legislative support for recycling and the circular economy continues to grow, especially in Europe. The UK will ban sales of new petrol and diesel cars and vans in 2030, and the EU plans to follow by 2035. Firms like Polestar and Volvo are already working with Circulor to ensure the ethical and sustainable sourcing of the

components required for battery-powered replacements. A new law comes into effect in 2023, with fines of up to 2% of annual group turnover, for companies with offices in Germany that don't do enough to protect human rights and the environment throughout their global supply chain. Regulators in Europe and beyond will try both carrot and stick approaches to nudging consumers and manufacturers toward products that consume fewer resources to make, have longer useful lives, and are easier to eventually recycle or repurpose.

- **Product-as-a-service revenue overtaking hardware sales.** Rolls-Royce introduced its first power-by-the-hour contract in 1962, and its civil aviation division now gets more than half its revenue from service-based offerings — but that's still unusual. As connectivity, compute, and sensors become cheaper, more manufacturers have begun to explore shifting from selling hardware to delivering services. With shorter innovation, development, and sales cycles than Rolls-Royce faced and a broader addressable market than in the airline business, many manufacturers will see more service than product revenue by the end of this 10-year period. And, as leaders at TOYO Tires discovered, the service shift may be fundamental to ensuring survival in a market where previous differentiators matter less than they once did.
- **Responsible approaches to AI helping people trust machines.** Predictive recommendations for maintenance, the optimization of hundreds of variables to derive the "golden batch," and most product-as-a-service offerings have one thing in common: They aren't feasible without machine learning and AI. But most of today's AI algorithms are effectively black boxes; no one really knows what's happening inside, hampering adoption. It's difficult for customers to trust recommendations they can't audit, especially when acting costs money. Bosch, Microsoft, and Rolls-Royce have published codes of ethics to guide responsible use of their AI. Over the next few years, EU member states will need to enforce a broad set of provisions from the EU's linked AI and machinery regulations, which give legal weight to requirements around AI's auditability, explainability, ethicalness, and trustworthiness across at least 27 countries.
- **Digital twins breaking out beyond single use cases.** Digital twins are a digital representation of a physical object's data, state, relationships, and behavior, and they have been powering separate design, process, and support use cases for 20 years. Technical advances and the breakdown of organizational silos will finally lead to digital twins that realistically follow the digital thread from product design to manufacture, use, and disposal. In the medium to long term, these more complex digital twins will overtake today's asset- and use-case-specific siloed deployments; they will unlock efficiencies, insights, and customer relationship

improvements by maximizing the value of data throughout an asset's life.

- **Digital industrial platforms spanning the IT/OT divide to deliver insight at point of need.** OT vendors dominate plant-floor systems in manufacturing, while IT vendors in most industries dominate top-floor systems. Both sets of vendors are pushing across the IT/OT divide, keen to extend the reach of their own solutions. Manufacturers increasingly need business solutions that support both IT and OT stakeholders, enabling interoperability and encouraging the breakdown of organizational silos. Forrester calls this emergent category a digital industrial platform, and we expect to see credible commercial examples emerge and gain market share during this period.

Innovation In The Longer Term Will Be Customer Led And Technology Enabled

Over the longer term (i.e., more than a decade from now), some of the bigger transformations will begin to play out. In responding to complex external pressures, manufacturers will use technology to deliver the sustainable, cost-effective, and resilient solutions their customers demand. We predict that:

- **The robots will keep getting more capable, while we place a premium on human craft.** Hardware and software automation will continue to improve and begin taking on the creative and adaptive tasks once reserved for humans. New, predominantly "lights-out" factories will become common. Some will be almost fully autonomous with a small human workforce; others will rely on remote humans for teleoperation. Handmade products will become even more desirable, attracting premium prices for those able to pay. Established factories with older equipment and workflows that are less easy to automate will become increasingly uncompetitive.
- **Manufacturers and their customers will tiptoe into the age of mass customization.** The convergence of easy access to data about demand, data about supply, and an increasing ability to retool and repurpose lines for relatively small batch sizes will lead us to fully embrace the age of mass customization. Were he running his company in the 2030s, Henry Ford might promise customers, "Any color you want. Period." But then again, maybe he wouldn't. Growing awareness of the environmental cost of a consumerist society will finally begin to change customer behavior: Personalized short-run products will elicit disdain rather than delight unless they have genuine utility, such as tools that properly fit the user. The larger opportunity may be to customize with software, not hardware.

- **Dirty manufacturers will start moving off-planet.** Moving polluting industries off the planet is not a new idea, but it received fresh attention when Amazon founder Jeff Bezos began talking about it. Moving heavy industry into orbit and perhaps securing raw material from lifeless asteroids may address many of our pollution and resource problems, but it raises fresh challenges for which we don't have good answers: How do we control emissions from the fuels used by a new generation of reusable rockets? How do we deal with inevitable accidents on the way up or down? How do we overcome gravity for the heaviest of heavy industries? But companies like Blue Origin and SpaceX are productizing launches and beginning to uncover the answers. Bezos believes that the move to orbit will take decades. Over the next 10 years, it should become clear whether the opportunity is sufficiently lucrative, compelling, and safe to keep chasing.

Supplemental Material

Additional Contributors

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