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EXECUTIVE SUMMARY

What will the manufacturing industry look like in the future? In the next 10 to 15 years, factories and plants across industry sectors will be high-tech engines of mass customization, able to respond quickly and effectively to changing customer and market demands.

Highly automated and information-intensive, the factory of tomorrow will look like an integrated hardware and software system. This system will be fueled by vast quantities of information from every corner of the enterprise and beyond, moderated by analytical systems that can identify and extract insights and opportunities from that information, and comprised of intelligent machines that learn, act, and work alongside highly skilled human beings in safe and collaborative environments.

Today’s image of manufacturing as a dark, dirty, and unattractive place to work will give way to a bright and exciting new reality. This reality is in the early stages of formation today as trends such as connectivity and networking, information and process digitization, advanced analytics and computing, and new models of production like 3D printing take hold and play out.

The vision of the future is bright indeed, but it is one that has vast implications as well as challenges. As manufacturing becomes increasingly connected and information-intensive, every functional aspect of the enterprise is likely to be affected, from design, to manufacturing through supply chains, and extending to customer service and support. Along the way, the skills people will need for manufacturing jobs may require significant change. Many manufacturers will have to undertake significant cultural, organizational, and management changes if they are going to take advantage of the opportunities offered by the digital revolution.

Moreover, manufacturers will need to be confident that the high-tech, connected world in which they will be doing business will become more safe and secure. They will also need to be sure that their intellectual capital, operations, and people will be protected. Increasingly, organizations becoming more reliant on automated decision making will need to be confident in the integrity of the information they use.

There will be multiple variations and differences in how digitization will apply in the many and varied sectors that make up the manufacturing industry. The pace at which companies adopt and learn to use digital technologies effectively will also vary. But the broad trends evidenced will likely affect all.

Specifically, the key trends and developments the Factories of the Future project identified are:

• Digitization is transforming how manufacturers need to think about human capital management. The workforce will need greater digital literacy and to have high-tech and collaboration skills. It will also need to be able to work cross functionally as well as with increasingly intelligent machines to bring higher levels of efficiency and productivity to the enterprise.
• Future factory designs and footprints will likely favor modularization, with micro factories capable of mass customization using such technologies as 3D printing as well as digital manufacturing technologies.

• The manufacturing innovation process will evolve to be more open and extended, with collaborative models that span internal as well as external constituencies.

• Supply chains will become highly integrated, increasingly intelligent, and even self-managing.

• New business models incorporating outcome-based services will emerge, enabling manufacturers to diversify their revenue streams and provide greater value to customers.

• Cognitive computing and analytic techniques will enable production environments to self-configure, self-adjust, and self-optimize, leading to greater agility, flexibility, and cost effectiveness.

All in all, the factory of the future will be a very different place than it is today as the industry renews itself for the digital age.

RESEARCH METHODOLOGY

Manufacturing Leadership Council members expressed an interest in developing a specific vision for Factories of the Future. This interest was motivated by the manufacturing transformation underway as a result of technology disruptions, business model innovations, and the broader vision of Manufacturing 4.0/Industry 4.0. The focus of the research was to examine this transformation for the general manufacturing industry with a glance at low-volume, high-mix industries as well. This white paper outlines the framework, evolution horizons, scenarios, and strategic imperatives.

Research Methodology

The research methodology deployed to develop the Vision 2030: The Factory of the Future report included the following:

• Frost & Sullivan proprietary industry databases and published research on industry transformations;

• Expert interviews with academic members of the Manufacturing Leadership Council’s Board of Governors, technology experts, sponsor/portfolio companies, and other industry ecosystem participants;

• A framework of industry transformation themes and developing scenarios for industry evolution with key technology enablers and business accelerators;

• Brainstorming with industry experts (internal and external) and manufacturing practitioners to validate scenarios;
• A live, two-day workshop with industry participants, including representatives from Intel and General Electric and several other Fortune 100 companies. Three companies GE Ventures has invested in -- Optomec, Sight Machine, and Upskill (formerly APX Labs) -- also participated in the workshop.

To synthesize the vision for the Factories of the Future, the first step was to develop a framework of appropriate Mega Trends and determine how their convergence would impact the scenarios of the future.

Mega Trends are transformative global forces that will define the future and will have a far-reaching impact on every aspect of business, society, and peoples’ lives. The steady march and convergence of these Mega Trends is accelerating industry transformations.

In order to develop a vision for the future of the manufacturing enterprise, it is important to consider the effects of several transformative forces. We have placed these Mega Trends into four major categories. We have also identified related themes and sub-themes that we believe will resonate across the manufacturing landscape over the next 15 years.

The major Mega Trends and their implications for manufacturers are:

• **Globalization/Urbanization/Regionalization/Uncertainty:** The interplay of global economic forces - particularly intense urbanization, regionalization, and globalization - is creating shifts in how manufacturers must think about how they design their production and supply networks. As globalization provokes responses such as the erection of trade barriers and as urbanization and the growth of regional economies lead to a demand for localized products and rising labor costs even in previously low-cost areas, manufacturers must continuously recalibrate where and how they produce, whether they outsource, and how they serve emerging markets.

• **Smart/Material/Open/Green:** New, smart approaches to innovation are on the rise. These approaches focus on waste reduction fueled by innovations in material science, open systems, and new forms of social collaboration. New collaborative relationships with customers and suppliers enable companies to rethink intellectual property protection strategies, and innovate at every level of the workforce.

• **Business Model Innovations:** The same technology forces that have convinced consumers to embrace sharing-economy-based businesses are transforming the industrial world. Smart, connected products and real-time analytics will allow manufacturers to sell outcomes - such as jet engine uptime - not just products. This means manufacturers will need to fundamentally rethink their relationships with customers. It also means they will face an entirely new competitive landscape.
• **Ambient Intelligence:** Advances in technologies such as cloud-based solutions, digital platforms and applications, machine learning, and the Internet of Things are combining to provide all institutions with the unprecedented ability to gain and act on insights. For manufacturers, this will bring the ability not just to recognize and respond to problems and opportunities in near-real time, but even the ability to predict them in advance and to act in an autonomous fashion. But first, manufacturers must fundamentally rethink governance and decision-making processes while also securing all systems and data.

Factories of the Future must evolve to address the changing realities of the Future of Enterprise. Figure 1 provides a reference to the framework for the development of Vision 2030.

**A FRAMEWORK FOR VISION DEVELOPMENT**

**Figure 1: Framework for Vision Development**

Factories of the Future in the Context of the Future of Enterprise
We see the interplay between these Mega Trends resulting in four major themes and eight sub-themes that, taken together, will transform the manufacturing landscape over the next 10-15 years. The new realities created by globalization and the opportunities afforded by new materials and social collaboration platforms, for example, lead directly to a major theme we call Intelligent Design.

- **Intelligent Design**

  Intelligent design embodies the move toward personalization and mass customization of products and the location of production closer to the point of consumption. It also involves the adoption of material science innovations and collaborative innovation processes. Advances in design software, cyber-physical encoding of information, blockchain, software-as-a-service, among others, are critical enablers.

  **The sub-themes are:**

  - **Federated Manufacturing.** Networks of smaller, more nimble factories that are better able to customize production for specific regions and customers will replace large, centralized plants. Apparel makers such as Adidas and car makers such as Local Motors are positioning themselves to move in this direction, leveraging technologies such as 3D printing. Manufacturers must understand how to retain efficiencies of scale while supporting unique and changing customer requirements.

  - **Smart Innovations.** Product design, production, and support processes will become much more integrated around the notion of the digital thread and digital twin capabilities that allow product characteristics and performance to be better understood and improved throughout the life cycle. Manufacturers must introduce organizational structures and encourage collaboration to enable these concepts.

Meanwhile, the focus on the disruptive potential of Business Model Innovation, combined with new, smart, and collaborative approaches to innovation, are spawning the Services Revolution.

- **Services Revolution**

  The Services Revolution is characterized by the unbundling of the supply chain, and catalyzed by the Internet of Things, 3D printing, cognitive intelligence, digital platforms, digital twins, and digital threads. These will enable not just the creation of new value networks, but will also usher in a transition from product-as-a-service to anything-as-a-service models.
The sub-themes are:

- New Value Networks. Suppliers will transform from providers of parts to partners in “as-a-service” business models. This will require much more collaborative value networks as well as high levels of digital trust, enabled by security technologies such as blockchain-as-a-service.

- Outcome-based Services. As advanced sensors and cognitive analytics are used to validate product performance, services sold on the basis of usage and guaranteed outcomes become possible. Manufacturers of complex products that require service will take advantage of this model, but it will require them to develop new levels of customer-centricity.

And we see the Ambient Intelligence Mega Trend—which combines ubiquitous, cloud-based intelligence with Business Model Innovation—setting off a Platform Revolution that will reshape competition in many industries.

- Platform Revolution

Platforms have accelerated the “disrupt-collapse-transform” cycle across industries. Traditionally asset-intensive sectors are threatened by asset-light models. When coupled with the network effect, the power of connected platforms will allow machine learning of a different order. The transformative power of an anticipatory response to every business process will unleash an era of cognitive learning and improvements.

The sub-themes are:

- Connected Platforms. Enabled by IoT and cloud technologies as well as advanced, real-time analytics, products will become connected platforms, featuring a range of services that will deliver new revenue sources. Already, for example, auto makers such as Tesla are positioning their products as connected platforms on which services can be delivered.

- Cognitive Platforms. Connected products—or platforms—will collect vast quantities of usage, performance, and diagnostic data that can be used to improve next-generation designs. Longer term, on-board cognitive capabilities will anticipate user preferences and adjust product configuration and performance accordingly, in much the same way that Amazon presents purchase options based on past customer choices.

Finally, we believe manufacturing will experience what we call Human-to-Machine Convergence, a theme that is a direct outgrowth of the effects of Ambient Intelligence—particularly reflected by the arrival of collaborative and sentient robots in the workplace—and the unified workforce implications of globalization.
• Human-to-Machine Convergence

Significant challenges across geographic boundaries include the skills gap, the need to leverage machines for productivity gain as well as the need to repurpose the existing workforce for a more digitized future. This will require a considerable focus from governments, businesses and universities, which must rethink human capital transformations. Artificial intelligence advancements and robotic process automation hold immense promise, but are also viewed as threats to jobs growth. However, effective prioritization and policy innovation can help harvest transformative benefits and create new types of jobs.

The sub-themes are:

- Machine Dominance. The relationship between machines and humans in the manufacturing environment is rapidly evolving as robots transition from being programmed only to execute repetitive tasks to being collaborative and even sentient. As that transition takes place, manufacturers must prepare the human workforce for higher-level tasks.

- Human Capital Transformation. To overcome a looming skills gap and transition the current workforce to thrive in a more digitized future, manufacturers must clearly define the skills that will be required, take an inventory of current capabilities, and provide tools that enable self-training and skills certification.

Organizations can leverage the framework to help create a prioritized approach for their own transformations. The key findings that emerged from the research initiative helped outline technology and business accelerators that will propel the journey towards Vision 2030: The Factory of the Future.

KEY FINDINGS OF THE SUBTHEMES

FEDERATED MANUFACTURING

Today, most manufacturers conduct operations in a centralized or partially decentralized way. Moving forward, however, many will attempt to modularize their operations, supported by a more horizontal structure that allows for greater customization of products.

The future state, in the next 10-plus years, is for the establishment of so-called micro-factories that, for example, will enable significant levels of personalization using 3D printing and digital manufacturing techniques.
A fundamental requirement for a digitized manufacturing process, especially one whose supply chain involves a considerable number of outside partners, is information security. Manufacturers must be confident that they have appropriate and effective cyber security policies, measures, and defenses in place.

Blockchain technology, a ledger of transactions that can be shared in a digital network, is expected to help support and enable transactions and traceability within a future network-of-factories model. The network model will also be characterized by open hardware designs; secure, cooperative supply chains; and a royalty model for shared designs.

The future state envisioned by digital manufacturing, with micro-factories producing customized products, holds the potential to have a significant positive impact on the industry as it continues to globalize and strives to meet customer requirements. A successful transition to the future state paradigm will also produce potentially significant financial benefits to companies that implement and use digitization well.

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<th>SECTOR</th>
<th>EVOLUTION STAGE</th>
<th>DESCRIPTION OF KEY TECHNOLOGY ATTRIBUTES</th>
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<tr>
<td>Centralized Manufacturing</td>
<td>• Hierarchically Structured</td>
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<tr>
<td></td>
<td>• Mass Production (N = Many)</td>
<td></td>
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<tr>
<td></td>
<td>• Product Design-to-Platform</td>
<td></td>
</tr>
<tr>
<td>Modular Manufacturing</td>
<td>• Horizontally Structured</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Customization (N = Few)</td>
<td></td>
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<tr>
<td></td>
<td>• Platform Innovations-to-Systems Innovation</td>
<td></td>
</tr>
<tr>
<td>Micro Factories</td>
<td>• Network Model</td>
<td></td>
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<tr>
<td></td>
<td>• Personalization (N = 1)</td>
<td></td>
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<td>• Systems Innovation-to-Product Innovation</td>
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SMART INNOVATION

The evolutionary path for innovation in manufacturing is a route that spans product, system, and material improvements. Achieving success along this path will require individual companies to employ collaborative innovation techniques with partners, use insights from analytical systems, and cooperate with government and academic institutions.

The desired future state of innovation in manufacturing is envisioned to be one that is open and achieved by leveraging a company’s full ecosystem. This ecosystem consists of partners, customers, and various outside institutions. It also requires the extensive use of advanced analytical tools, crowdsourcing techniques, and the automation of the innovation process itself.

Like in other areas, the digitization of the innovation process will require intrinsic levels of cyber security to create and maintain trust in the system. But it will also require clarity about intellectual property ownership. Companies that engage in multi-partner innovation activities will have to decide who owns the inputs and outputs of that process. There will have to be appropriate financial incentives for ecosystem partners to collaborate. Perhaps the most significant challenge, however, is to be found in the internal, existing cultures of companies. Many manufacturers will have to undertake a cultural shift in order to accept the idea of collaborative innovation, a shift that must have the support of top management.

But to reach this desired future state, many parts of the innovation process will also have to change. Manufacturing will have to adopt and learn to effectively use new IT tools to help manage the innovation process. Moreover, manufacturers will have to become truly customer-centric in their innovation processes. They will need to entertain ideas and suggestions from the outside, perhaps even crowdsourcing inputs. This amounts to a cultural challenge for many companies to overcome and an organizational challenge to figure out how and when to incorporate outside insights into the innovation process itself.

In addition, manufacturers will have to develop partnering and collaboration skills and processes to a much greater extent than they have before. This multi-tiered activity will require new financial investments, the sharing of ideas and information with third parties, and people and resources to manage information, interactions, and actual collaboration. And manufacturers will need to do all of this with the confidence that their intellectual property will be protected and can be monetized.
Digitizing and improving the innovation process will require a lengthy, multi-year effort in many manufacturing companies. Acquiring new IT tools to aid that journey will be the easier part. The more difficult challenges lie in reinventing the innovation process itself through collaboration and openness.

But the payoff for individual companies and the industry at large is potentially substantial. The “network effect” of industry collaboration could raise all boats in the industry.

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<tr>
<td>Smart Innovations</td>
<td>Product/System/ Material Innovations</td>
<td>• Product-Oriented Innovations</td>
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<tr>
<td></td>
<td>(Power of one)</td>
<td>• Perfecting 3D Printing Materials and Processes</td>
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<td></td>
<td>Collaborative Innovations</td>
<td>• Tight/Closed-Loop Innovation</td>
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<tr>
<td></td>
<td>(Power of few)</td>
<td>• Leveraging Big Data Insights</td>
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<tr>
<td></td>
<td>Open Innovations</td>
<td>• Collaborative Tools and Critical Data Sharing</td>
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<td></td>
<td>(Crowdsourced/open/AI)</td>
<td>• Open Innovations</td>
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<td></td>
<td></td>
<td>• Leveraging Cognitive Technologies for Next-Order Innovation</td>
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<td>• Embedded Security and Ubiquitous Digital Trust</td>
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NEW VALUE NETWORKS

Many manufacturers are in the process of trying to better integrate their supply chains in order to be more responsive to changing conditions and to reduce inventory and lead times.

As more and more elements of the supply chain become connected and as data generated via the connections provide insights to management, manufacturers can achieve higher levels of visibility and control over the entire extended supply chain or network. Strategies based on Internet of Things enablement will support these objectives.

The evolutionary path for supply chains is to build upon more extensive connectivity and integration in order to achieve higher levels of resilience. This will enable supply chain systems to react, adapt, and perform with unprecedented agility, speed, and cost effectiveness.
As digitization of the supply chain proceeds and matures, the next level of sophistication will combine the use of analytics and artificial intelligence tools to create supply chains that behave more autonomously, even healing themselves when demand- and- supply problems occur. Moreover, these highly automated supply networks will use advanced technologies such as cognitive bots, simulation, and inference engines to automatically manage purchases, which will likely be supported by some form of blockchain technology that can ensure security and inspire digital trust.

To enable the future state, manufacturers will need, at a very basic level, iron-clad cyber security as they migrate to cloud-based platforms to manage their supply chains. The right infrastructure to do this will require extensive connectivity, point-level data collection, and capabilities for data analysis.

On the ecosystem front, manufacturers will need to come up with new incentives for supply chain partners and also figure out how to leverage industry/government/academic consortia. The potential impact on the industry as supply chains evolve to this higher order could be transformative.

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<tr>
<td>New Value Networks</td>
<td>Integrated Supply Chain (Improved Visibility + Limited Recourse)</td>
<td>• Dark Data Integration Through Use of IoT&lt;br&gt;• Cloud-Enabled Supply Chain Visibility&lt;br&gt;• Supplier Assessment and Selection; Risk Assessment and Modeling</td>
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<td>Resilient Supply Chain (Full Visibility + Full Recourse with Human Assist)</td>
<td>• IoT-Enabled Supply Chain Visibility&lt;br&gt;• Cognitive Insight for Exception Event Management and Optimization&lt;br&gt;• Supplier Rationalization and On-Demand Alternative</td>
</tr>
<tr>
<td></td>
<td>Self-Healing Supply Chain (Full Visibility + Automated Recourse)</td>
<td>• Digital Twin Moves to the Edge (enabled by Digital Thread)&lt;br&gt;• Cognitive Bots with Self-Authorization&lt;br&gt;• Embedded Security and Ubiquitous Digital Trust</td>
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**OUTCOME-BASED SERVICES**

When manufacturers think about how they might change their business models to create new or greater value, the idea of being able to price and charge for outcomes associated with services is one that holds great appeal when considered in the context of how to truly deliver outcomes. This contrasts with just engaging in product- and spare parts-based transactions with customers.

Today, the basic business model for many product manufacturers is one in which customers pay based on a product’s specification. Manufacturers use traditional technologies to measure, validate, and record specification parameters.
The evolutionary path is to IP-enable products that enable the gathering of critical data about a product’s condition and performance. This data can then be used not only for preventive maintenance, but also to make product improvements through a 360-degree automated product lifecycle process.

This will lead to a business approach under which the financial model can change to one based on a product’s usage, enabled by analytics. Ultimately, the revolutionary model is one based on customers paying for agreed-upon outcomes from products.

To do this effectively, the industry must develop sector-specific standards for outcomes as well as usage metrics, liability models to manage risks and failures, and traceability approaches across the value chain to verify outcomes delivered. Determining how to measure value in a standard way is a significant challenge with the outcome-based model that industry will have to solve.

But moving to this model could have a profound impact on how products are conceived, made, sold, and used, with significantly different revenue streams for product manufacturers.

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</table>
|              | Pay for Specification | • Factory and Onsite Inspection for Specification Verification  
|              | (Cost +)              | • Cloud Analytics for Performance Improvement  
|              |                       | • Data and Connectivity Issues                                                                       |
|              | Pay for Usage         | • Ability to Measure In-service Performance  
|              | (XaaS)                | • Actionable Edge Analytics  
|              |                       | • Data Accuracy, Authenticity and Automatic Redress Mechanism                                         |
|              | Pay for Outcome       | • Ability to Measure Outcomes  
|              | (Outcomes)            | • Cognitive Analytics at the Edge  
|              |                       | • Embedded Security and Ubiquitous Digital Trust                                                      |

CONNECTED PLATFORMS

As more and more functional areas of the manufacturing value chain become interconnected and begin to generate insights from data, manufacturers will go through a process of learning how best to collect, process, analyze, and make decisions based on the collective intelligence of the extended enterprise.

The typical analytical process journey manufacturers will go through—almost a journey of discovery—has several dimensions: descriptive, diagnostic, predictive, prescriptive, and, finally, cognitive.

This process of discovery will be overlaid and applied to data from the Internet of Things as well as digital twin and digital thread models. The evolutionary path leads to ambient intelligence.
The level of intelligence generated from digital twins and digital threads will be important contributors to enabling manufacturers to become much more agile and flexible operationally. The challenge is in implementing such a broad and pervasive digitization scheme that spans from the edge through the fog to the cloud. This will require significant cultural and organizational changes on the part of manufacturers.

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<tr>
<td>Connected</td>
<td>Reactive Internet of Things</td>
<td>• Augmented Intuitions</td>
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<td>Platforms</td>
<td>Predictive Internet of Everything</td>
<td>• Cognitive Decision Making</td>
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<td></td>
<td>Anticipatory Internet of Lifecycle</td>
<td>• Ability to Query Through All Data Sources</td>
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<td>• Seamless Connectivity</td>
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<td></td>
<td>• Ambient Intelligence—Closely Coupled with Customer/Product Lifecycle (Leveraging Internet of Lifecycle)</td>
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<td>• New Technologies Enabling Connectivity for Ambient Intelligence</td>
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**COGNITIVE PLATFORMS**

As applied to manufacturing production, manufacturers today are employing analytical systems to mine data generated from ERP, MES, and PLM systems to improve production efficiency, product design, and asset management.

Over the next five to 10 years, the analytic discipline applied to production will evolve and mature. In parallel, production environments will change with the addition of technologies such as 3D printing, collaborative robots, automated guided vehicles, and other advances. The single biggest transformation will be incorporating data from digital twins, enabled by digital threads, to build learning into multi-generational products.

Cognitive analytics and computing techniques, which bring together natural language processing, problematic reasoning, machine learning, artificial intelligence, and other technologies, will enable production environments to self-configure, self-adjust, and self-optimize. Much greater production flexibility, agility, and adaptability are expected to result. But manufacturers will have to ensure they have or have access to the right IT infrastructure to support cognitive capabilities that can seamlessly understand and infer lessons from field deployments and build them into next-generation products.
These technologies, if successfully implemented and used by a broad cross section of industry, have the potential to move the entire industry forward to an advanced state of continuous learning and intelligent entities never before seen, with consequent competitiveness and financial benefits. But the challenge of adopting and employing these technologies should not be underestimated. They will require significant changes in staffing and in the decision-making processes of companies.

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<tr>
<td>Cognitive Platforms</td>
<td>Digital Manufacturing (Sub-System level)</td>
<td>• Integrated Production Systems&lt;br&gt;• Analytics-Based Product Design&lt;br&gt;• Predictive Asset Maintenance</td>
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<td></td>
<td>Adaptive Digital Manufacturing System (System of systems level)</td>
<td>• Intelligent Production System&lt;br&gt;• Advanced Analytics-Aided Product Lifecycle Management&lt;br&gt;• Operation Performance Updating Digital Twin for Process Optimization</td>
</tr>
<tr>
<td></td>
<td>Cognitive Manufacturing Platform (Adaptive AI-reinforced system of systems level)</td>
<td>• Cognitive Manufacturing Processes&lt;br&gt;• Multi-Generational Cognitive Insights-Enabled Product Lifecycle Management&lt;br&gt;• Embedded Security and Ubiquitous Digital Trust</td>
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**MACHINE DOMINANCE**

There is little disagreement that the factory of the future will be highly automated. Many tasks and functions still being done by human beings today will transition to intelligent machines and devices that will perform them.

A variety of technologies will be employed in this transition. These include increasingly intelligent and capable robots that can work side by side with people, automated guided vehicles that can move materials around, augmented and virtual reality systems, and networked plant floor equipment. Overlaying all of this will be extensive data collection and deep analytics. And a fundamental requirement will be iron-clad data security and safety.

Automated machines, in place in many organizations now, enable continuous workflows in design, production, and inspection. Collaborative machines, typified by robotic systems that can work alongside humans, are already on some manufacturing floors. The projected future state, though, is around sentient machines, which are machines that are self-aware and capable of responding to and even anticipating changing conditions.

There are a number of requirements that need to be in place before this future state can be realized. Standards to support interaction between machines and between machines and humans will need to be developed. Software that facilitates understanding in the machine/human environment will need to evolve. Manufacturing companies will need to redefine jobs and processes, and provide training for new roles. And manufacturing workers will, over time, have to adapt to working alongside robots.
It almost goes without saying that the impact of a new generation of intelligent machines in factories and plants will have profound consequences on how production is conducted, the role of people in the production environment, and efficiencies that companies may achieve with the higher-order machines, including evolved robotics.

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<th>EVOLUTION STAGE</th>
<th>DESCRIPTION OF KEY TECHNOLOGY ATTRIBUTES</th>
</tr>
</thead>
</table>
| Machine Dominance       | Automated Machines | • Configurable/Flexible Workflows  
                        |                                                             | • Configurable Robots  
                        |                                                             | • Integrated Manufacturing Process                          |
|                         | Collaborative Machines | • Automated Material Routing  
                        |                                                             | • Collaborative Robotics  
                        |                                                             | • Augmented Manufacturing Process                           |
|                         | Sentient Machines (Machines' ability to think & interact with cognitive platforms) | • Digital Twin Moves to the Edge (Enabled by Digital Thread)  
                        |                                                             | • Self-Configurable Work Platforms, Adaptable to Workflow  
                        |                                                             | • Cognitive Manufacturing Process                            |

**HUMAN CAPITAL TRANSFORMATION**

Digitization is the change agent now coursing through the manufacturing workforce.

In order to realize the benefits of digitization, manufacturers require workforces comprised of people who can use and leverage advanced technologies. These technologies include augmented and virtual reality systems, artificial intelligence systems, Big Data analytics, and new production platforms like 3D printing, to name just a few.

The evolutionary path to realizing workforce transformation includes understanding the many dimensions of the journey forward. First and foremost is creating a digital awareness and culture that will enable workforces to accept the digital way of doing things in both brownfield and greenfield environments. This will require manufacturing companies to invest in digital change management for an extended period of time.

On the technology front itself, manufacturers must leverage advanced technologies such as analytic tools and advanced robotic systems to augment labor, improve training, and extend and increase automation. These changes will require manufacturers to redefine job roles and responsibilities, and rethink their performance measurement systems. Additionally, this digitally savvy workforce must learn to trust intelligent machine decisions that may be counterintuitive to the more traditional production environment.

The industry can indeed transform its workforce to meet both the opportunities and challenges of the digital era, but this will require transformative approaches and new ways for people to collaborate with machines. After all, the industry has always needed and will continue to require smart, skilled people to move it forward. The digital era is no different but will require advanced technology skills and the ability to work collaboratively and cross-functionally within the manufacturing enterprise.
CONCLUSIONS

The general outlines of what future factories and plants will look like are now discernable. They will be organized for greater speed, flexibility, productivity, and efficiency. The people who work in them will be highly skilled about advanced digital technologies and able to work cross-functionally across the connected enterprise.

The underlying trends compelling these changes appear to be inexorable. Rapidly changing and increasingly sophisticated information and operational technologies are facilitating a shift to mass customization, from mass production, making it possible to satisfy individual needs from transportation to medicine. Pervasive digital connectivity is generating vast new quantities of information about every functional aspect of the manufacturing enterprise, the products and parts that are made, and the customers to which these products are sold. As a result, new worlds of insight are emerging into how manufacturing processes and manufactured products can be improved, how unmet customer needs can be addressed, and how new business models and opportunities for manufacturers can be identified.

Despite protests from some quarters, the globalization of manufacturing, powered by the relentless march of technology, will continue, leading to what some have envisioned as the coming Internet of Manufacturing.
Of course, this highly connected, information-driven paradigm will not play out in identical fashion in every sector that makes up the diverse industry called manufacturing. Some sectors, such as aerospace and defense, will continue to require huge centralized factories and extended supply chains to produce their large products, but even they will be affected by mass customization desires. On the other side of the spectrum, consumer product goods companies will be increasingly focused on providing local production capabilities to serve their markets. And vehicle manufacturers will do the same, albeit with as much platform commonality as possible.

In the decade ahead and beyond, factories and plants will be distinguished by a now-evolving set of technological and organizational characteristics that will clearly identify them as different from factories and plants of prior eras. Some of the characteristics are:

- Information-intensive and highly automated;
- The ability to be agile, flexible, and reconfigurable to meet the demands of mass customization;
- Highly connected and integrated electronically in order to properly orchestrate the enterprise’s effective management of information about its processes, products, and intellectual property, and the knowledge of its workforce and its customers;
- Capable of effectively collecting, analyzing, and using in its decision-making processes the enormous amounts of data that are being generated from pervasive connectivity; and
- Highly productive and sustainable.

The extent and depth of change underway will make it seem, at times, as though the industry will be in the throes of completely remaking itself. What could be more awe-inspiring, and even perhaps a bit frightening, than the notion that human beings would work alongside machines that could learn, think, and act? The convergence between people and intelligent machines will be as revolutionary as the advent of mass production techniques a century ago. Quantum leaps in productivity and efficiency will result.

An expanded analysis of the major themes emerging from the research reveals the following:

**INTELLIGENT DESIGN** – Under this theme, increasing advances in material science innovations, coupled with exponential approaches to accelerating innovation through collaborative and open processes, will transform the ideation process. This will require mechanisms to allow IP protection as well as new monetization approaches, so that the ecosystem can have incentives to help create solutions and collaborate. Mass customization and micro-factories will drive disruptions in the way we design and execute manufacturing.
SERVICES REVOLUTION – Advanced technology developments such as IoT, cognitive bots, and blockchain-as-a-service, all supported by ubiquitous digital trust, will enable new value networks, spurring a Service Revolution. These networks will promise not just full seamless visibility, but increasing degrees of automated recourse and corrective action. With digital twins moving to the edge (i.e., where assets are) and with advance sensors that validate performance parameters, cognitive analytics can be performed at the edge. This will enable the offering of advanced services based on usage and improved outcomes.

PLATFORM REVOLUTION – Advanced computing, IoT, specialized platforms, cloud, and machine-learning technologies have brought about the ability to reinvent past processes and eliminate wasteful practices through the enablement of cognitive insights. These transformations, coupled with elements of business model innovations, will accelerate the Platform Revolution. Connected platforms will allow for the Internet of Lifecycle (the ability to review performance data through the lifecycle using advanced cognitive technologies), incorporating learning into digital twins for next-generation products.

HUMAN-TO-MACHINE – This convergence will drive automation and help address the challenges of workforce skills gaps. Advanced training will become available through the use of augmented reality and virtual reality systems, helping to remove the dependency on human labor to perform routine, repetitive, and dangerous jobs. As advanced, self-configurable workflows and cyber/physical systems take over, human capital transformation efforts will have to be undertaken by corporations, governments, and society. The key takeaway from the H2M convergence trend is that society and individuals will have to devise unique approaches to enable the acquisition of higher-order skills. Rather than viewing the transformation as a threat to traditional manufacturing jobs, the approach toward addressing demographic and skills issues will require unprecedented innovation on all fronts.

Overall, future factory models will change dramatically as manufacturers ride the wave of mass customization. Depending on industry sector and type of product produced, manufacturers will design their factory footprints in myriad ways, from micro-factories positioned to serve local markets to mega-factories designed to make the largest and most complex products. The thing they all will have in common, though, is the ability to operate with a far greater level of operational intelligence and flexibility as a result of the new and emerging technologies.

But achieving this glittering future factory state will not be easy, inexpensive, or linear. Manufacturers will have to carefully adopt and learn to use effectively a vast array of new technologies, ranging from augmented reality systems to 3D printing machines. They will have to architect their systems comprehensively for the future, while implementing gradually. They will have to plan investments wisely based on clear business and market plans, and establish return on investment models that they can live with. And they will have to be willing to experiment to see the possibilities in the new digital age and from time to time accept failure on their journey forward. For many, massive cultural and organizational change is on the horizon.
But perhaps the most important requirement for success in the age of digital factories will be trust, the confidence that the pervasive connectivity now underway will not result in theft, interruptions or damage, and that the information that will be increasingly relied upon is indeed true and accurate. Moreover, workers will need to trust that their companies will provide training that will enable them to transition to the digital way of doing things. And nations themselves will need to trust that the shift to automation, often in response to global trends, will not create unacceptable societal disruptions.

Throughout the ages, trust has been perhaps the one truly indispensable ingredient for business. It will be no different for manufacturers in the digital age.
GLOSSARY

**DATA LAKE:** The data lake principally is an approach toward a unified, enterprise-level, single-data store (ranging from raw data, to semi-processed and proceeded data). Legacy attempts were fraught with challenges, causing delays in insights from data either due to siloed systems or batch-oriented approaches to data retrieval. Newer approaches allow for streaming analytics and online access that have improved access to timely insights.

**DIGITAL THREAD:** The digital thread is the creation and use of a digital surrogate of a materiel system to allow dynamic, real-time assessment of the system’s current and future capabilities to inform decisions in acquisition. The digital surrogate is a physics-based technical description of the system resulting from the generation, management, and application of data, models, and information from authoritative sources across the system’s life cycle. (Extracted from DOD SAF/AQR Definition).

**DIGITAL TWIN:** A digital twin refers to a computerized model of a physical asset or a process. The model can be used to monitor, discover, diagnose, and forecast future states based on its ability to represent a mathematical compute of the physical state, often measured by sensors that collect data on a device’s ongoing physical conditions.

**INTERNET OF LIFECYCLE:** The phrase “Internet of Lifecycle” refers to the ability to collect, assimilate, and improve the design of next-generation products through the constant analysis of operational data from digital twins. Over a multi-generational product lifecycle, the digital thread is a key enabler, helping to improve the fidelity of the digital twin and allowing product developers, users, and data scientists to help leverage the power of the Internet of Things to collect data about products/systems and improve their design.

**CLOSED-LOOP INNOVATION:** Closed-loop Innovation is an approach that leverages a predefined network of partners/suppliers/sub-suppliers to help with the innovation of products, platforms, and networks. Complex rules redefine the IP protection, and system levies do not necessarily incentivize innovation. Open innovation leverages a more inclusive approach, and system levies are reduced/redefined to help incentivize the power of collaborative innovation.
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