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3D Opportunity

Additive manufacturing paths to performance, innovation, and growth

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3D Opportunity

Additive manufacturing paths to performance, innovation, and growth

BY **MARK COTTELEER** AND **JIM JOYCE**
> ILLUSTRATION BY **TANNER GRIEPENTROG**

Additive manufacturing (AM) has exploded into public consciousness over the past several years. More popularly known as "3D printing," AM is an umbrella term for a group of technologies that creates physical products through the addition of materials (typically layer by layer) rather than by subtraction (e.g., through machining or other types of processing).[1]

Stories and perspectives appear in the popular press and technology blogs on a daily basis. Enthusiasts tout the prospect for AM to revolutionize manufacturing industries and the markets they serve. Skeptics point to the relatively limited number of uses and materials in current practice and to the relatively small impact these technologies have had outside of a few niches. Critics raise concerns about applications (e.g., 3D printed guns) and the inevitable intellectual property issues that the increasing adoption of AM technologies will create.[2]

ADDITIVE MANUFACTURING DEFINED

Additive manufacturing is an umbrella term for a set of technologies and processes nearly 30 years in development. These technologies have reached a level of maturity that increasingly allows for the existence of value-added commercial applications. Some see AM as an innovation driver that can literally transform manufacturing industries over the next decade.

The American Society for Testing and Materials (ASTM) International, a globally recognized leader in the development and delivery of international voluntary consensus standards within the manufacturing industry, defines additive manufacturing as:

"A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."

In common practice, the terms "AM" and "3D printing" are used interchangeably.

The reality of AM incorporates some balance of these views. AM is an important technical innovation whose roots go back nearly three decades but whose strategic relevance has risen sharply. This technology breaks existing performance trade-offs and expands the realm of possibility in two fundamental ways. First, AM reduces capital required to achieve scale economies. Second, its flexibility decreases the capital required to achieve scope economies.

Using AM to break the constraints of these trade-offs creates opportunities for companies to improve performance, grow, and innovate. Understanding how this can be accomplished requires a review of how scale and scope economies shape the decisions that managers make about the manufacturing and distribution of their products.

CAPITAL VS. SCALE: MINIMUM EFFICIENT SCALE SHAPES SUPPLY CHAINS

AM promises to reduce—more so over time—the minimum efficient scale that gave rise to large modern industrial production facilities, lowering barriers to entry into manufacturing.

Prior to the late 1700s, the majority of production took place among local artisans serving nearby communities. Production was labor intensive and small-batch oriented.[3] Transportation over large distances was slow and sometimes perilous. Then came the Industrial Revolution. Technology was invented to harness the power of water, steam, and then electricity. New chemical and manufacturing processes allowed for more efficient production on a large scale. New transportation and communication networks facilitated coordination and delivery over long distances. The result was an extraordinary expansion of economic activity and living standards for most of the Western world.

The change wrought by the Industrial Revolution altered the fabric of industry itself. New technologies required large amounts of capital to develop and deploy. In order to justify such investment, similarly large quantities of product were required to amortize the investment over many individual units of production. Thus, the era of mass production was born. This era is characterized by large-scale, centralized, industrial operations that arose as a result of the technical capability to exchange capital for labor.[4]

The relationship between capital and scale is captured using the concept of minimum efficient scale—the point at which the average cost of each unit of production is minimized. Where minimum efficient scale is high (i.e., where there are large capital costs required to initiate production) the number of production facilities will be small.

AM impacts the economics of production by reducing minimum efficient scale. In some cases, AM may allow consumers to satisfy their individual needs without the significant labor or capital investments that might have previously been required. Research supports this conclusion. Multiple economic studies illustrate that minimum efficient scale for AM can be achieved at low unit volumes—as low as one. This cost performance contrasts with that of traditional manufacturing methods that face higher initial costs for tooling and setup.[5]

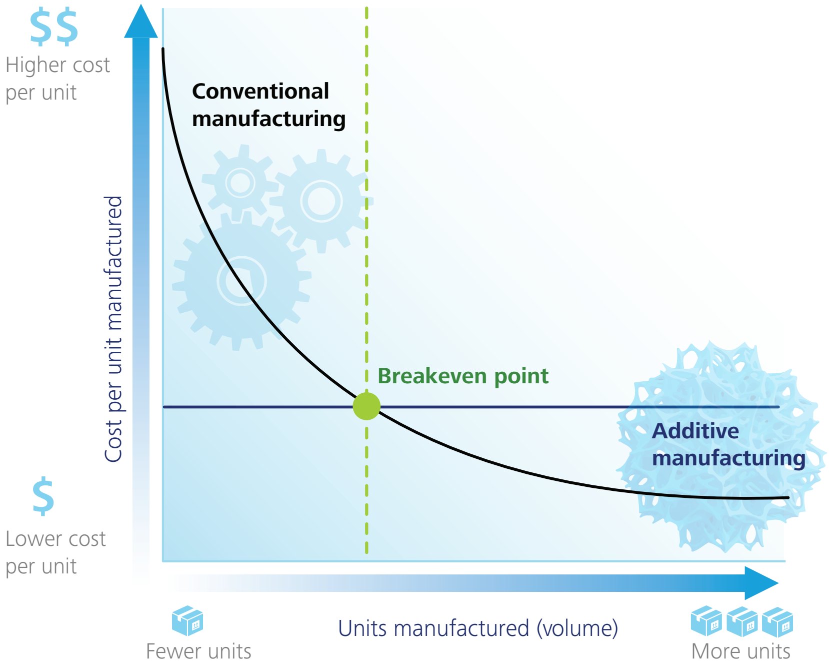
Figure 1 illustrates a prototypical set of cost curves for AM and traditional manufacturing methods drawn from existing studies. The cost curves illustrate the change in average cost for each incremental unit of production. Breakeven between two alternative production approaches occurs where these curves cross. Figure 1 illustrates the achievement of minimum efficient scale for AM manufacturing, in this case, at one unit.[6] In essence, the average cost curve is flat, suggesting that marginal cost does not change with volume. More traditional production methods may as yet yield cost advantages at higher volumes, as suggested by the declining cost curve.

The research concludes that AM production, using a variety of materials, can provide an efficient alternative for low-to-medium-sized production runs. Furthermore, expected reductions in material costs leave open the potential for breakeven points to substantially increase in the future.[7] Improvements in throughput and reductions in the cost of AM equipment can only serve to further amplify these effects, increasing the production quantities at which AM might compete with more traditional manufacturing methods.

CAPITAL VS. SCOPE: ECONOMIES OF SCOPE INFLUENCE HOW AND WHAT PRODUCTS CAN BE MADE

The impact of AM technologies on scope economics may exceed their impact on scale. Within the constraint of available materials, AM is known to be

Figure 1. Breakeven analysis comparing conventional and additive manufacturing processes



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extremely versatile in its ability to produce different product configurations with reduced changeover time and cost.[8]

Economy of scope refers to the inherent flexibility of a unit of capital. Specifically, scope economies deliver advantage by allowing for the production of multiple different end products using the same equipment, materials, and processes.[9] Unit cost falls as the number of products that can be made using the same invested capital increases.

Scope economics may also facilitate production approaches that are impractical or impossible through traditional manufacturing methods. For example, design for manufacturability rules advocate for simple designs with fewer parts.[10] However, traditional manufacturing processes often impose design limitations that can proliferate the number of parts required to produce a product or component. As the geometric complexity of a component increases, it can prevent a part from being fabricated as a single piece. Issues of internal accessibility or surface configurations may prevent desired machining approaches.[11]

Furthermore, complex geometries, including the fabrication of internal features, are more easily handled with AM.[12] The case of GE Aircraft and its use of AM to produce fuel nozzles for its next generation LEAP (aircraft) engine provides a good example of manufacturing capabilities. In this case, GE was able to manufacture, as a single unit, a component that previously required the welding together of 20 small pieces. The AM approach for the new part led to reduced labor and scrap while yielding a part with lighter weight—a critical attribute for fuel-conscious airlines.[13]

PRACTICAL IMPLICATIONS OF AM-INDUCED SHIFTS IN SCALE AND SCOPE ECONOMIES

The scope impact of AM is a result of the technology's flexibility. In many cases, no changes to tooling are required to shift the AM device from producing one object to producing a totally different object (i.e., AM could sequentially produce a sword and then a plowshare without alteration to the production equipment).[14] Changeover time is reduced, and potential variety expands. Just as important, the increased scope that AM technology affords can enable the production of entirely new components, which cannot be created by any other means. Combined with AM effects on minimum efficient scale, this implies that a relatively low capital investment could substitute for a wide variety of higher-capital-intensity applications when applied to appropriate contexts. Furthermore, these contexts may be more geographically scattered than traditional manufacturing approaches allow—essentially democratizing manufacturing by making it accessible at a much lower investment level.

The implication of changes in scale and scope economies is that manufacturers may be able to produce products with potentially dramatically lower capital costs. This will naturally lead to an opportunity to employ more productive locations, each at a smaller scale, as companies optimize logistical costs or take the opportunity to serve new or distant markets. The ability to do so may have profound implications for the speed with which customers can be served—or manufacture for themselves—and the accuracy with which demand can be met. These conclusions have direct practical implications for managers. In essence, it allows them to evaluate the applicability of AM to their operations by framing the choice relative to its impact on a company's supply chain and/or its products. In other words, companies can use AM to reconsider the ways they move products through their supply chains, and they can use these technologies to create new products or reengineer processes for making existing products.

Framing the AM investment choice in this way presents companies with four tactical paths to follow as they deploy these technologies across their businesses:

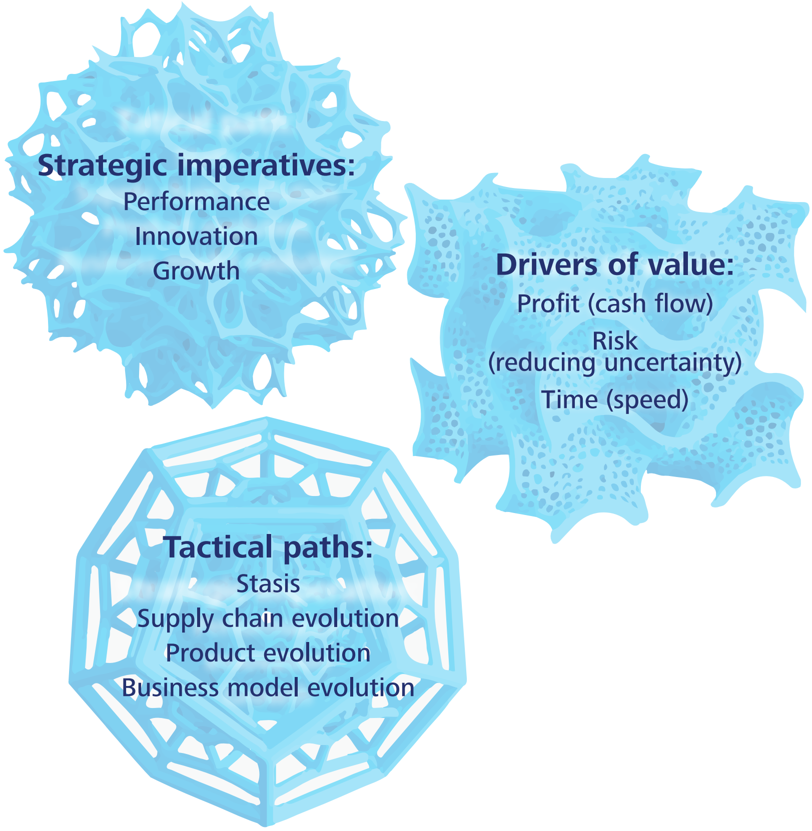
- **Path I:** Companies will not seek radical alterations in either supply chains or products, but they may retain interest in exploring AM technologies to improve value delivery for current products within existing supply chains.

- **Path II:** Companies take advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the products they offer.
- **Path III:** Companies take advantage of scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer.
- **Path IV:** Companies alter both supply chains and products in pursuit of new business models.

PERFORMANCE, INNOVATION, AND GROWTH: STRATEGIC IMPERATIVES FOR AM

Company leaders recognize that it makes little sense to pursue either supply chain or product changes in the absence of an overarching strategic imperative that defines the need to follow whichever path they choose. Therefore, when selecting a path, it is critical to understand if it is likely to lead to satisfaction of the chosen imperative. In general, such imperatives fall into one of three main categories: performance (the accomplishment of an objective relative to identified standards and relevant trade-offs), innovation (a combination of activities or

Figure 2. AM strategic imperatives, drivers of value, and tactical paths



Graphic: Deloitte University Press | DUPress.com technologies that breaks existing performance trade-offs in a way that makes new outcomes possible), or growth (an increase in revenues that results from a set of management choices).

In addition, company leaders need to determine the ways in which value is likely to be delivered. Once again, it is crucial to understand whether the path chosen is likely to yield value for the company in the ways it seeks. Business value is generally recognized to be an explicit mathematical function of three drivers: profit (changes in cash flow delivered through cost reduction or revenue enhancement), risk (the likelihood that cash flows will materialize), and time (the speed at which cash flows can be realized).

Consideration of the alternative paths that companies can follow as they integrate AM into their operational and business models, along with the strategic imperatives they pursue (performance, innovation, and growth), offers a means for gathering insight on the kinds of value that can be expected from each combination of choices and goals. Figure 2 summarizes the dimensions of this challenge. A better understanding of how these choices build toward the delivery of AM value is possible through an analysis of the activities to which we are already seeing AM put to use.[15]

Figure 3. Framework for understanding AM paths and value

Path III: Product evolution

- **Strategic imperative:** Balance of growth, innovation, and performance
- **Value driver:** Balance of profit, risk, and time
- **Key enabling AM capabilities:**
  - – Customization to customer requirements
  - – Increased product functionality
  - – Market responsiveness
  - – Zero cost of increased complexity

Path IV: Business model evolution

- **Strategic imperative:** Growth and innovation
- **Value driver:** Profit with revenue focus, and risk
- **Key enabling AM capabilities:**
  - – Mass customization
  - – Manufacturing at point of use
  - – Supply chain disintermediation
  - – Customer empowerment

Path I: Stasis

- **Strategic imperative:** Performance
- **Value driver:** Profit with a cost focus
- **Key enabling AM capabilities:**
  - – Design and rapid prototyping
  - – Production and custom tooling
  - – Supplementary or "insurance" capability
  - – Low rate production/no changeover

Path II: Supply chain evolution

- **Strategic imperative:** Performance
- **Value driver:** Profit with a cost focus, and time
- **Key enabling AM capabilities:**
  - – Manufacturing closer to point of use
  - – Responsiveness and flexibility
  - – Management of demand uncertainty
  - – Reduction in required inventory

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ANALYZING THE TACTICAL APPROACHES TO VALUE DELIVERY WITH AM

We conducted an analysis of the strategies, tactics, and value of AM approaches through a review of existing academic studies and available case examples. Some cases were derived from publicly available information. In others, case data was derived from information provided by clients and industry partners. Through our analysis, we attempted to identify the critical outcome sought by companies through the application of AM technology (e.g., reduce weight, improve fit, better match demand, etc.). We also sought to identify the tactical objectives (i.e., the path) being pursued as well as the strategic objective (performance, innovation, or growth). Finally, we assigned each outcome to a driver of value (improved profit, reduced risk, or reduced time). The results of our analysis are presented in figure 3 and described in the following sections.[16]

PATH I: STASIS—A STARTING POINT FOR ADDITIVE MANUFACTURING

AM offers opportunities to deliver improvement for targeted areas of performance in companies, independent of any desire to significantly alter products or supply chains. It is on this stasis path that the technology has gained its foothold and contributed value over the past 30 years, being most commonly deployed for modeling, prototyping, tooling, and short-run production.[17]

A key performance enhancement offered by AM is the ability to streamline and accelerate the design process. The result of this can be a reduced time to market, improved product quality, and reduced cost.[18] For example, the ability to print complex designs using stereolithography (one of the oldest and most common AM technologies) is used in the aerospace sector for producing engine parts, wings, and other design components for flight tests.[19]

Efforts have also delivered value by producing lower-cost tooling and other fixtures used in production.[20] For example, jewelry manufacturers use AM to reduce the lead time on the creation of assembly jigs, while aerospace manufacturers use it to print masking for parts in their chroming and coating processes.[21]

In general, performance-enhancing efforts related to path I deliver value by improving profitability through cost reduction and by accelerating the speed with which the resulting cash flows can be delivered (by accelerating the business cycle). That deployment of AM in pursuit of these goals requires neither dramatic supply chain nor product redevelopment to deliver value and provides a relatively lower-risk starting point for firms interested in integrating these technologies.

If a company is trying to improve its competitiveness with little risk and limited change, AM can play an important role in addressing the speed and profitability of its current operational model.

PATH II: SUPPLY CHAIN EVOLUTION—AM IN PURSUIT OF PERFORMANCE AND GROWTH

Similar to path I (stasis), the supply chain evolution path presents significant opportunities to improve performance, this time through supply chain transformation. Primarily, the derived benefits come from AM's ability to significantly reduce minimum efficient scale in production locations, alter traditional supply chains, and reduce working capital requirements.

Among the key promises of AM in redefining supply chain operations is the potential to impact field service operations and "long tail" inventory. These applications can simultaneously deliver performance improvement on all three drivers of value: profit (cost), risk, and time. For example, the military is experimenting with the use of AM in field surgical hospital settings. In one demonstration project, the military sought to deliver on-demand production of medical and surgical instruments in remote sites.[22] The business case for the demonstration project identified challenges associated with availability (time to delivery), logistical limits on quantity and variety (cost), matching supply and demand (risk), and the ability to provide sterile instruments in field settings due to equipment limitations (cost of capital).

Evolution in supply chains is also evidenced at the business-to-consumer level with multiple big-box retailers and other service providers leveraging scale and scope economies to deliver on-demand printing at local sites. For example, UPS started putting AM capabilities into local franchises in an effort to service the prototyping needs of small businesses.[23] It is the specific shifts in minimum efficient scale enabled by AM that enables this business model. In the long run, such shifts in supply chain structure may represent a key growth vector, as firms large and small try to capitalize on the ability to deliver faster, cheaper, and more precisely than their competitors.

PATH III: PRODUCT EVOLUTION—AM IN PURSUIT OF PRODUCT INNOVATION

True innovation opportunities prominently arise along path III, where the capabilities delivered by AM, in some cases, allow for the creation of physical products that cannot be produced by other means. The previously mentioned GE aircraft fuel nozzle for next-generation LEAP technology aircraft engines is an outstanding example. The ability to combine 20 different subcomponents into a single build is made possible only by the additive process that the technology affords, regardless of cost.

In addition, AM technologies are increasingly allowing the use of multiple materials and the ability to embed sensors, electronics, and other technologies within components and products. The US military has demonstrated capability in this

Figure 4. Example of photorealistic depiction of collectibles by Cubify

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PHOTO: DAVID CLUGSTON

area, embedding strain gauges and other sensors within aerodynamic structures in order to monitor performance and wear. Embedded designs can also extend to the use of conformational cooling channels for thermally conductive materials.[24] Such designs can be used to more efficiently dissipate heat during casting and other manufacturing processes.

The scope economies provided by AM technologies enable a variety of new custom-product alternatives that might be used to create and expand markets that otherwise could not economically be served. 3DMe™ by Cubify, for example, represents one of a number of new product companies built around the ability to place photorealistic depictions of individuals on custom collectibles and other products (see figure 4 for an example).[25] Apparel companies are also getting into the act. For example, researchers have demonstrated economical approaches for improving footwear performance using AM.[26] Footwear manufacturers are putting this and other insights to use, for example, in the development of custom manufactured spike plates tailored to individual runners' biomechanics in designs not possible with traditional manufacturing.[27]

The product evolution path (path III) also presents some opportunities to improve performance. Current applications suggest that performance value is derived as much or more from the mitigation of risk as from the enhanced speed and profitability that factor so heavily along paths I and II. This opportunity comes from the ability to improve product fit, customize tooling, and monitor the build process in ways that are not possible using other methods. For example, AM technology has established a strong foothold in a variety of medical device sectors through its ability to tailor the design of individual implants (e.g., dental crowns and hearing aids) to the needs of individual consumers. The impact of AM on such applications is considered inevitable.[28]

PATH IV: COMBINED SUPPLY CHAIN AND PRODUCT EVOLUTION—AM IN PURSUIT OF BUSINESS MODEL INNOVATION

Path IV companies try to apply AM in either sequential or simultaneous transformations of both products and the supply chains that deliver them. In essence, they seek to combine the tactics and value embedded in path II and path III to achieve not only the operational advantages that define new levels of competition, but also to create new business models. In many cases these simultaneous efforts represent attempts to create new ways of delivering value in an effort to deliver growth opportunities in a manner that either creates new markets or impairs competitors' ability to compete.

For example, Symmons Industries, a maker of bathroom fixtures, transformed its supply chain by creating channels to directly interact with its customers in the design process for items such as doorknobs and cabinet handles. The company uses the results of this collaboration to develop and manufacture new, custom-made products to the market.[29]

Similar attempts to simultaneously transform both supply chains and products are underway within the health care industry where AM technologies are rapidly shifting approaches to medical planning and execution. Advancements in imaging combine with the ability to deliver low-cost, multi-material AM technologies to the point of use in medical clinics in ways that reduce costs, accelerate the delivery of services, and improve quality.[30] In health care, the strategic imperative may be more related to innovation in the delivery of services to patients than to growing the overall segment.

It is reasonable to posit that the route to path IV runs through the product innovation goals that characterize path III. The delivery of innovative products may require new or revised approaches to supply chains and distribution, or it may present opportunities to disrupt competitors and markets when combined with supply chain innovation (e.g., highly customized dental crowns being manufactured at the dentist's office). This may be particularly true where AM and digital technologies are deployed to increase the level of collaboration between producers and end users. Non-AM aspects of the production process (e.g., affixing spikes to a shoe) may determine where physical production is likely to take place, but disintermediation of middlemen may turn out to be a feature of the resulting supply chains.

> While managers can expect the AM technology space to continue its rapid evolution, the industry dynamics we have identified will not change. Their direction seems set. As AM technologies advance and their costs fall, their impact on minimum efficient scale, and therefore the ability to proliferate production sites and alter supply chains, is likely to accelerate.

WHERE TO START

AM represents an innovative technology that breaks two trade-offs that helped define the structure of many industries dating back to the Industrial Revolution. These technologies have the effect of significantly reducing minimum efficient scale in impacted industries while simultaneously expanding the available scope economies (due to their flexibility). As a result, managers are presented with intriguing choices about how to extract available value. Four key paths to value present themselves. The choice of which path to start on depends, in large part, on the strategic imperatives and the drivers of value that managers seek, and they may be affected by the industries and sectors in which they compete.

If a company is trying to improve its competitiveness with little risk and limited change, AM can play an important role in addressing the speed and profitability of its current operational model. We refer to this as the path I "stasis" approach. Companies can follow this path while developing experience integrating AM with current operations and supply chains. We view this as lower risk because there is no attempt to change critical aspects of supply chains or products. As the traditional path to initial value in the employment of AM, path I offers the benefits, for example, of accelerated product development, reduced waste, and improved part performance through better design.

Where companies are concerned with the competitiveness of their supply chains, path II offers a different type of value opportunity. Here, companies may seek opportunities to improve performance more than to innovate. AM technologies offer the benefit of value delivery related to cost and time. Reductions in minimum efficient scale may allow production to be distributed more broadly than in the past, requiring fewer stages and participants in a supply chain. Flexibility and distribution of production offer opportunities to collapse supply chain response time and allow for an improved ability to match supply and demand for both standardized and custom products. The ability to enter new geographies with lower capital investment may also offer important growth prospects at lower levels of overall risk.

Path III is for companies in which the discussion is about product innovation and the functionality and benefits delivered by their products. Here the scope economies offered by AM come into full view. Greater manufacturing flexibility, the decreasing cost of part complexity, and the opportunity to deliver higher functioning products offer the prospect of true product innovation. New product offerings can trigger new growth cycles as improved products reach new customer segments and geographies.

Path IV exists as a combination of efforts and derived value related to path II and path III. However, while the value derived from paths II and III can be characterized as raising the competitive standard for value delivered by a supply chain or product, the combination of both avenues of value improvement have the potential to redefine operational models and produce new business models that disrupt the basis of competition (rather than merely raising the standard of competition).

While managers can expect the AM technology space to continue its rapid evolution, the industry dynamics we have identified will not change. Their direction seems set. As AM technologies advance and their costs fall, their impact on minimum efficient scale, and therefore the ability to proliferate production sites and alter supply chains, is likely to accelerate. As the flexibility of the technology increases, through the addition of materials and processes, the scope economies of AM will grow, creating opportunities for new products and innovations. In particular, firms that offer products with complex internal geometries that are restrained by technical limitations in machining should pay close attention to developments related to AM.

The opportunity for companies to apply AM in the pursuit of value through improved performance, greater innovation, and accelerated growth will remain for the foreseeable future. DR

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Endnotes

1. See sidebar "Additive manufacturing defined," p.6, for more information about the terms "additive manufacturing" and "3D printing." Source for additive manufacturing definition is ASTM International, *Standard Terminology for Additive Manufacturing Technologies. Designation: F2792–12a*, 2013, p. 2.
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15. To be sure, there are those that will argue AM technologies will be used in ways that we have yet to imagine. The veracity of this claim does little to alter what we can learn about the value and direction of AM from current applications.
16. In some cases, it can be argued that these applications exist on a spectrum. For example, at some point the ability to improve weight and part performance, an example of a path I objective, may transition to a more fundamental innovation in the component, migrating to path III. Our categorization, in particular, depends on an understanding of where to draw a distinction between whether AM provided capability pushes the company closer to the "state of the art" as it exists across all industries (performance), or whether it redefines the state of the art in general (innovation). Regardless of the distinction, we believe the analysis offers some valuable insights.
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