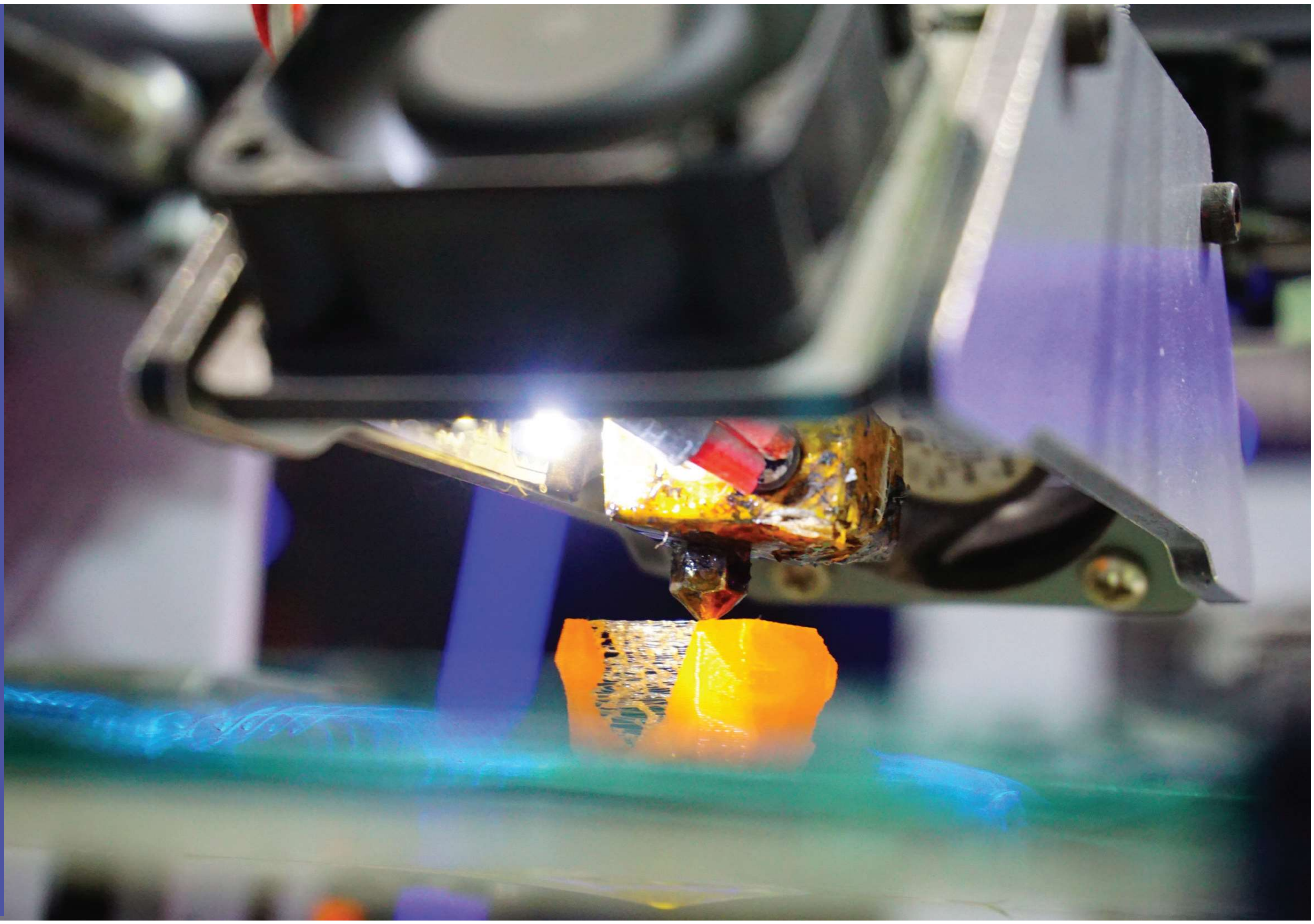
PRIME TIME FOR

ADDITIVE MANUFACTURING

Once a disruptive technology, 3D printing and additive manufacturing are ready to make the leap from the fringe to mainstream.

BY JAYANTH JAYARAM, ALAN AMLING, ATANU CHAUDHURI AND DAN MCMACKIN

Disruption is the rule in supply chain management and manufacturing today. Although conventional supply chains remain the backbone of global commerce, most observers expect convention to make way for fundamentally new processes such as manufacturing on demand that involve additive manufacturing (AM) and 3D printing. That's certainly our conclusion based on our research for this article, which included field studies of the customers of Fast Radius, a Chicago-based AM solutions company. Utilizing in-depth interviews with key personnel and a review of secondary sources, we've put together a best practices framework along with insights for supply chain managers who are considering AM in the context of their digital supply chains (see sidebar: About our research).



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The story of additive manufacturing is similar to other disruptive innovations that made the leap from the fringe to the mainstream, such as the Internet, electric cars and social sharing platforms like Uber and Airbnb. While AM has a nearly 40 year history, it's now poised to make that transition over the next decade. Capabilities and case studies continue to grow as the drawbacks to AM such as time, cost and material availability, continue to shrink. Forward-thinking companies such as GE, Seimens and Wassara are already reaping the benefits of AM (see sidebar: Putting 3D to work).

Early adopters aside, Industry 4.0 is forcing managers to think differently about where and how goods are manufactured and moved around the world. As a result, their digital offspring, aided by additive manufacturing (AM) and 3D printing, are gaining significant traction in the world of manufacturing and just-in-time fulfillment. Over the last decade, investment in AM research, technology and materials has skyrocketed. According to the 2019 Wohlers Report, the global AM market is expected to hit $15.8 billion in 2020, growing to $35.6 billion in 2024. This is dramatic growth from AM's humble beginnings in the 1980s.

Putting 3D to work

GE, Siemens and the Swedish mining company Wassara are examples of early adopters of 3D printing in the supply chain.

GE was able to combine 855 traditionally manufactured parts for its new Catalyst turboprop engine into five additively manufactured parts. This not only vastly simplified GE's supply chains but enabled a 20% lower fuel burn and 5 percent weight reduction.

Siemens is using AM to produce and repair critical gas turbine components like burner heads and swirlers. In one AM initiative, Siemens combined 13 parts into a single part, resulting in a 25 percent weight reduction. In another, fuel and air pipes that were placed outside the burner in conventional models, could now be routed internally, greatly reducing the risk of damage and leaks. AM also generated savings in fuel consumption, improved efficiency and the performance benefit of a strong cooling effect thanks to improved air flow. This reduced the temperature by up to two-hundred-degrees Celsius, which is noteworthy because a mere 10-degree reduction substantially increases the life span of turbine blades.

Wassara uses high-pressure water to power Down-The-Hole hammers that extract minerals with minimum environmental impact. The complexity of the existing design leads to expensive parts and frequent rejects in production as a result of the joining process. It also lends to failures due to wear and corrosion. Using AM, Wassara redesigned the hammer's sliding case, simplifying complex fabrication steps such as drilling cross-holes that require one end to be blind plugged or welded and chose a new material alloy of maraging steel. The additively manufactured sliding case showed no signs of corrosion and only minimal wear compared to a standard part.

AM adoption

AM represents a fundamental change to the traditional store and ship model. Rather than manufacture and store what a company thinks the consumer wants, goods can be produced and shipped on demand—based on what the consumer is ordering. This allows for customization, and for new designs that are not always possible with traditional manufacturing. Other benefits include parts reduction, efficiency in supply chain management and improvements in product performance metrics, like reduced weight and improved quality. As the quality of products produced through AM increases and the cost of materials and production declines, an increasing number of goods will be produced more often, in lower quantities and closer to the point of consumption. That aligns supply with demand in a way never before possible.

AM also has significant potential to lower the risks involved in the launch of new products. Using AM, companies can very quickly shift from prototype to production to test the market for a new product with zero inventory risk. If needed, changes can be made quickly and in real-time. If it sells on the website, the company can similarly shift into production mode with 3D printing until sales justify a conventional production line.

The early stumbling blocks to the adoption of AM, such as an increase in manufacturing time and the cost and availability of materials, are fading. However, there are still practical challenges that must be considered to make the business case for AM.

For one, a manufacturer must understand the true cost of ownership of its products, including the dynamic stream of life cycle costs. What's more, the benefits of AM are often based on assumptions that must be validated. There is also likely to be resistance to change. In some companies, design personnel may be slow to accept the changeover. In others, it may be production personnel who have to be convinced. For those reasons, implementing AM involves the careful consideration of change management strategies across a variety of stakeholders. These will vary from one company to the next.

Customers may also play a pull or push role in adoption. In some instances, a customer may have a part it wants produced using additive manufacturing, pulling its supplier along. In other instances, a customer may be pushed into accepting 3D printed parts after an AM technology provider educates it on the benefits of additive manufacturing for its product—the push. Of course, pull and push approaches can be combined to offer total customer solutions support.

The new realities of AM

As the technology improves and the market gains experience with additive manufacturing, we have identified several new realities.

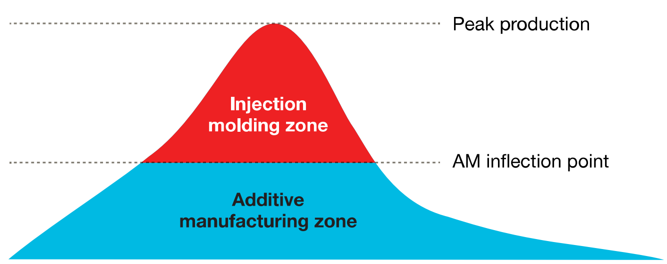
Additive manufacturing is more than a printer. The technology got its start in limited runs of consumer products and prototypes. Industrial production is where it's now headed. Consequently, metals showed the strongest growth of any AM material for the fifth straight year, growing nearly 42% in 2018 according to the Wohlers Report. However, industrial scale additive manufacturing is more than just the printer and materials. It represents an integrated ecosystem of processes and services. The same product design, using the same printer and the same material, could have vastly different costs and quality characteristics depending on the manufacturer. More advanced manufacturers have moved upstream to provide design and business planning services to their AM customers, as well as downstream post-production, quality control and logistics support. For this reason, OEMs must not only certify each additive manufacturing partner, but also each product produced by that manufacturer. Consequently, AM marketplaces that merely match customers with AM suppliers may be a poor fit for industrial production, unless the marketplace under consideration certifies the suppliers and assures quality. Some of the more sophisticated service bureaus are trying to make the transition from prototyping to industrial production, but at this point, no service bureau has established a leadership position in industrial production.

Economies of scale and diseconomies of scale. The improved quality of final parts, along with increased throughput, make 3D printing practical for small and mid-scale manufacturing. In some cases, tens of thousands of units can be produced in a cost-efficient, timely manner compared to the cost of conventional manufacturing. This is enabled in part by the availability of a variety of improved materials. For instance, investment in the use of metal in AM has skyrocketed, with process improvements and new technologies driving down the cost per part. Similarly, there is a high degree of flexibility and versatility in the choice of materials. Today's additive manufacturing systems operate like Swiss Army knives, with a single piece of equipment able to perform dozens of applications. By working with a wide range of materials and switching between them, a single machine is capable of producing parts for many different applications. One of the best examples of this versatility is resin-based polymer 3D printing processes, like stereolithography (SLA). The same compact, desktop SLA 3D printer can produce biocompatible splints and surgical guides in a small dental office, as well as jigs, fixtures and temperature resistant molds for an automotive factory.

Lifecycle approach to additive manufacturing. The decision to employ AM does not need to be an "all-or-nothing" decision. An emerging approach to manufacturing is to use the most appropriate manufacturing method for different points in a product's lifecycle. In the early days of a product's life, that may be using AM for prototyping—some companies are also certifying AM for early production runs of some products when sales volumes are low.

However, as products mature and higher volume production is needed, AM will reach an inflection point where it makes economic sense to switch to traditional manufacturing methods such as injection molding. This inflection point will vary by product and application but is continuing to rise as material costs plummet and AM technologies improve. This concept is reflected in Figure 1 as the "injection molding zone." As the product reaches the end of life and volume drops below the AM inflection point, the most appropriate production method returns to the "additive manufacturing zone." Digital designs of replacement parts can be stored in virtual inventory, to be produced on-demand, improving service levels while dramatically lowering inventory holding costs.

FIGURE 1
AM inflection point



Source: Authors

Fast Radius

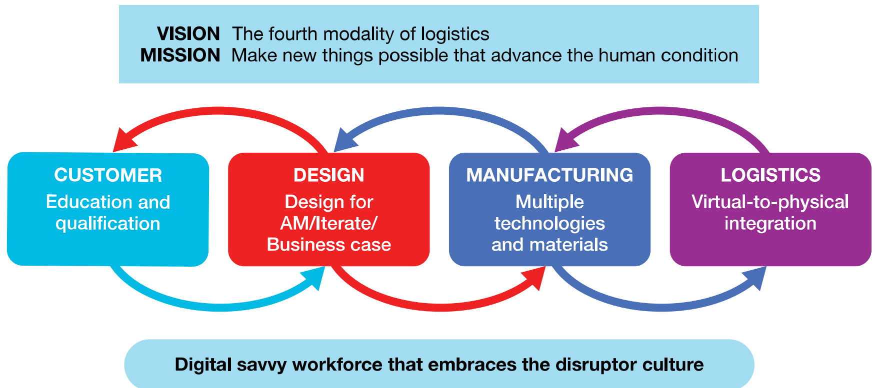
To better understand the state of AM today, we talked with Fast Radius, a Chicago-based contract manufacturer. Fast Radius along with its strategic partner, UPS, were the only North American companies identified by the World Economic Forum as one of the nine best manufacturers in the world implementing the Fourth Industrial Revolution (see sidebar: Fast Radius, a 3D innovator).

In Table 1, we describe six user cases from Fast Radius's customer base. They represent six different industries, ranging from the materials handling industry where Bastian is using 3D printing to manufacture components for its robotic picking arms to the outdoor power products industry where Husqvarna Group is manufacturing parts for its products.

Based on the breadth of industries and customers served by Fast Radius, we've developed the following take-aways on how to build a successful business model around an AM-enabled supply chains. We call this the "anatomy of a disruptor" (Figure 2).

FIGURE 2

Fast Radius: Anatomy of a Disruptor



Source: Authors

The foundation

Fostering a technology disruptor culture. The foundation of this model is built on digitally savvy employees who integrate diverse capabilities along the digital thread, coordinated through a compelling vision and mission. But it's more than that: A key enabler of a successful AM platform is a culture of technology disruption. A dynamic, forward-looking corporate culture helps achieve this disruption mindset by attracting and retaining young and energetic engineers who are technology savvy. These engineers are driven by an opportunity to see real contributions to their client's bottom line and are often extremely motivated and focused on growing their careers along with the growth of the company. These tech-friendly engineers generally strive to be part of a young, ground-breaking company. Many of these employees are "digital natives" and do not need to "unlearn" the design limitations of traditional manufacturing methods.

Fast Radius considers itself to be "technology and material agnostic." Currently, it uses four primary technology providers in its factory (HP 3D Printing, Carbon, Stratasys and Desktop Metal) with dozens of material options. That enables Fast Radius to match the right printer technology and material to each application.

Fast Radius, a 3D innovator

Fast Radius is an additive manufacturing innovation partner based in Chicago. It helps companies discover, design, make and fulfill products that are uniquely enabled by AM or through a combination of manufacturing processes. This enables the company to offer new supply chain solutions through a combination of virtual warehousing and a mass-customization approach geared toward final assembly solutions, or to entirely re-design new products. Once these applications are identified, Fast Radius manufactures and fulfills these products/solutions through global nodes of additive production.

Fast Radius is building an industrial-grade operating system to orchestrate the end-to-end workflow by digitally connecting these nodes. Making repeatable parts at scale with additive manufacturing is often compared to the complexity of semi-conductor and wafer fabrication processes. The Fast Radius OS allows it to deliver consistent, repeatable parts at nodes around the world, which are proximate to the locus of demand.

The top leadership at Fast Radius has referred to this Internet-enabled, distributed manufacturing model as the Fourth Modality of Logistics. According to those we interviewed at the company, AM will transform the Cloud into the Fourth Modality of Logistics, augmenting logistics transport by air, land and sea. Certain goods will be transported by "data over the Internet" to distributed production sites, as compared to a "parts on planes" approach.

TABLE 1

Comparison of case studies using Fast Radius services

COMPANY NAME	INDUSTRY	PROBLEM FACED	AM SOLUTION APPROACH	OUTCOMES
BASTIAN	Material handling	Design and manufacturing of a material handling system that can handle a wide variety of product shapes, sizes, and densities without having to invest additional capital in multiple custom grippers for the picking arms.	By using 3D printing for critical parts (around 50% of BOM), Bastian Solutions can quickly scale the robot arm for its customers' requirements. Once the adjusted design is submitted to Fast Radius' Virtual Warehouse, the customer receives the additive parts in days instead of weeks or months. This helps customers get their new materials handling systems up and running with little interruption to their business. An example of such a part in the system is a proprietary "Shark Fin" adaptive gripper using Carbon® Digital Light Synthesis™ and EPU 40 material. Carbon's material enabled Bastian Solutions to develop a unique set of fingers that are strong but pliable–capable of picking up anything from a laundry detergent bottle to a tube of lip gloss.	Lightweight equipment, improved energy efficiency, rapid manufacturing of custom parts, significant project time and cost savings.
CURTISS	Bike	The complex parts were difficult to produce using CNC machining with long lead times. The new unique bike needed to go into production quickly.	The engineers at Fast Radius worked with Curtiss to make their designs ready for manufacturing. Together, they created parts that could be manufactured while still adhering to Curtiss' high design standard. The Fast Radius team evaluated all of the part requirements and created a hybrid solution that comprised three separate production processes, including legacy and additive methods.	2 days reduction in lead time compared to any other supplier, 95% first-pass yield for the 60 parts produced by Fast Radius.
STEELCASE	Furniture	There was a need to expand the personalization options for the SILQ chair and continue to reimagine the design. Steelcase wanted to explore how additive manufacturing could improve the product development process and differentiate their products in the market, while also greatly reducing the time it took to bring the product to life.	Steelcase™ partnered with Fast Radius and Carbon® to design, engineer, and print a custom arm cap using additive manufacturing processes. Fast Radius designed the additive manufactured arm cap in four zones that provided different attributes based on how someone's arm might interact with the cap. Although each zone was designed separately, Carbon®'s DLS™ technology allowed the entire arm cap to be printed as one cohesive part using EPU 41, a material that is both flexible and conforming. And the use of lattices reduced material usage by up to 70 percent without sacrificing performance.	Streamlined product design and development; Improved and unique aesthetics; Simplified the assembly by consolidating three parts into one; Improved customer experience through mass customization at scale.
COAPT	Medical device	Upgrading production to the next generation of 'complete control' systems required retooling of systems software as well as redesigning hardware components. Speed to meet product release time was vital.	Fast Radius used patented additive processes to print 36 unique designs yielding 195 parts for the customer to evaluate for functional use. Producing at this rate of prototypes quickly helped Coapt get their own finished products faster to the market. It also further tested their testing ability at a fast pace.	Reduction in print time of end-use parts; Increase in print parts per print; Reduction in weight of a part; Increase in the rigidity of a part.
COBALT ROBOTICS	Producing security robots	Finding a cost-effective supplier that could deliver on the exact specifications of the part.	Fast Radius helped on the cosmetic parts of the robot machines. Specifically, they helped manufacture critical parts using urethane casting. They recommended new CNC master patterns that were more accurate compared to Cobalt's original FDM ones that had fitment issues.	Saved 62% on the cost of urethane casting; Saved 33% on the cost of 3D printing; Saved 90% on the cost of painting and finishing; Saved 7% on the overall cost of robot production.
HUSQVARNA GROUP	Outdoor power products	Identify parts that can be made more efficiently and sustainably through AM.	Fast Radius helped screen parts and narrow down parts that could be produced at a larger scale and yet of good quality using AM. Furthermore, they identified the most appropriate AM technologies (in this case, Multijet Fusion (MJF) and Carbon Digital Light Synthesis (DSL)) which are best suited to produce the parts based on price and performance needs.	Reducing carbon footprint through less materials waste; Improving spare parts fill rates; Lowering inventory carrying costs.

Source: Authors

Capabilities

Customer education. Fast Radius has found large gaps in the awareness of AM capabilities within its existing and prospective clientele. These gaps pertain to different AM technologies and equipment. A second key gap is evaluating the business case needed to justify AM.

Gaps in awareness of AM and justifying the ROI through metrics are two of the key factors in AM deployment. Therefore, Fast Radius conducts tailored workshops among a small group of prospective clients. These workshops typically result in clients signing up for dedicated engagements with Fast Radius on AM projects.

Fast Radius helps enterprise clients adopt AM through its proprietary Application Launch Program (ALP). The six-month program helps companies identify applications, validate business cases, develop designs and prototypes, test and certify the applications and prepare to scale.

Building unique qualifying process for AM. This idiosyncratic process gives Fast Radius a competitive edge, and clearly positions it as a better value-added partner compared to service bureau firms whose product/service portfolios are rather limited. The competitive advantage of an idiosyncratic qualifying process is that Fast Radius is able to offer life cycle support and quality assurance of its AM parts and processes. Also, it helps by offering suggestions on new SKU creation and old SKU retirements on a dynamic basis.

Building the business case. As noted earlier, building the business case for AM can be a challenge. To help customers address this challenge, Fast Radius educates them on a process called Total Value of Additive (TVA). The TVA concept is similar to Total Cost of Ownership (TCO) but applied to AM. While the cost of materials remains a primary driver of AM unit cost, TVA includes all costs, such as new product development (NPD), supply chain, re-design costs after launch and carbon footprint reduction. On the revenue side, incremental revenue is considered as well as brand impact, customer experience, capturing otherwise foregone opportunities, compressing NPD cycles and functional improvements (such as deweighting and parts consolidation). Considering the impact on supply chains from minimum order quantities and inventory holding costs for low volume service parts could flip the equation in favor of AM.

Iterative design and material-agnostic solutions. Fast Radius is representative of a new breed of AM manufacturer that understands a customer's needs first and then finds the most appropriate manufacturing method, technology and materials through an iterative design process. It's end-to-end customer-oriented solutions range from digitization all the way up to spare parts delivery on demand to remote locations across the globe. Fast Radius has found that an AM solutions provider must help customers choose an appropriate path of adoption over time. On many occasions, the solution calls for a mix of traditional and AM processes to be used. Fast Radius facilitates both for its customers.

Building data science capability. Through interactions with clients, Fast Radius gathers large amounts of data. These interactions take the form of problem-solving for specific projects identified by clients (the pull approach we discussed earlier). They also prompt new directions for the customer using a push approach. The latter is partly driven by analyzing the huge data set captured through end to end discussions with customers.

As Fast Radius develops recipes to turn CAD drawings into high-quality parts, the information gathered during the design and production phases creates a virtuous circle of information that continually improves those processes. A key challenge in the industrial adoption of AM is an assurance of quality throughout the process. Using data from its printing machines, Fast Radius can predict the failure of a build before it is fully completed, and then rectify the design as a part moves through the production process.

Virtual-to-physical integration. While products can be modified in infinite ways

About our research

Open-ended and guided interviews were conducted with Fast Radius, a leading additive manufacturing company. Interviews included the CEO, COO, chief marketing officer, director of manufacturing and supply chain, chief application engineer, additive/traditional manufacturing solutions manager and the chief designer. Each interview lasted approximately 30 minutes. The topics covered ranged from strategic long-term issues to customer/application-specific strategies, and also included a component of forecasting future trends in AM. These interviews coupled with published customer testimonials (case studies) formed the basis of this work. Further clarifications on themes emerging from the interviews were sought from the company. The resulting and updated best practices framework is reported in this article.

Readers can learn more about the state of additive manufacturing from the following:

"Additive manufacturing revolution for gas turbines," by Niels Anner, siemens.com.

"Co-creation and user innovation: The role of online 3D printing platforms," by Thierry Rayna, Ludmila Striukova and John Darlington, *Journal of Engineering and Technology Management*.

"Digging deep with Wassara," published on Renishaw.com/en.

in the virtual world, we live in a physical world. Optimizing the best of both worlds requires integrated capabilities. AM holds the promise of manufacturing goods in smaller quantities, closer to the point of consumption, allowing dramatic decreases in cost and carbon footprints. AM also allows products to be stored virtually as digital designs that can be printed on demand. All of this requires alignment with physical logistics services. To that end, Fast Radius has worked with global logistics provider UPS on a virtual warehouse solution. The Husqvarna case study in Table 1 is an early example of the virtual warehouse.

Vision for Industry 4.0. Vision is a soft term that is hard to measure, but the successful adoption of additive manufacturing requires top management with a vision and an understanding of how AM fits within Industry 4.0. It's particularly important to track any changes in the vision and to stay aligned with dynamic changes in the environment. For example, the original vision of Fast Radius's co-founders was to provide globally distributed manufacturing, on-demand. However, this original vision evolved into The Fourth Modality of Logistics, an idea that highlights AM's role in the emerging digital supply chain. This evolution encompassed end-to-end manufacturing of industrial parts and products, from design through delivery. This new vision enabled the company to leverage the unique capabilities of AM, including de-weighting designs, combining multiple parts into one and "making the unmakeable." This vision is supported by a mission to "make new things possible that advance the human condition."

The importance of a compelling narrative was supported by a recent article in the *Harvard Business Review* on the top 20 business transformations of the last decade by Scott D. Anthony, Alasdair Trotter and Evan I. Schwartz. The authors found that the common element between all 20 successful transformations was a narrative that infused a higher purpose into the culture and provided clarity to everyday tasks.

Moving AM forward

Fast Radius' efforts to help customers solve manufacturing conundrums utilizing additive manufacturing and 3D printing is an example of technology disrupting long-held processes and their underlying assumptions. More importantly, as more companies like GE, Siemens and Wassara adopt AM, the technology is poised to leap from the fringe into a mainstream. Savvy supply chain leaders will take the time to investigate where 3D printing and AM fit into their futures.