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Additive Manufacturing: Implications for Technological Change, Workforce Development, and the Product Lifecycle

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MIT work OF THE FUTURE

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Executive Summary

Additive manufacturing (AM)[1], commonly known as 3D printing, is a cornerstone of a responsive, digitally driven production infrastructure. Though AM has been used for prototyping for decades, it is reaching an inflection point as a mainstream, serial production process. Adoption of AM is improving product development efficiency, manufacturing execution, and product performance. It enables manufacturers to envision futures in which their products are fulfilled on-demand, customized to individual user or regional preferences, and fulfilled via an interconnected network of production facilities distributed around the world. AM also leverages computationally driven design approaches for shape optimization and development of materials with performance surpassing current benchmarks. The United States is well positioned to leverage AM technologies to grow its manufacturing sector's competency and competitiveness; according to most industry metrics, the United States has established itself as the leader both in AM entrepreneurship and its utilization.

Despite its strong industrial potential, the implementation of AM remains constrained by the technology's maturity and the skills of the corresponding workforce. Importantly, the fundamental economics of AM, at present, generally constrain its use cases – especially in volume – to those where the manufacturer can afford a cost premium for AM, such as for aerospace components, medical implants, and cosmetic products. This cost premium is offset by improved device performance or the identification of new modes of value delivery. By and large, such applications have required significant investment, and leveraged contributions of an ecosystem of educational institutions, industry stakeholders, and professional organizations.

Beyond its economics, the future growth of AM will be governed by growth in the range of materials it can process, as well as certification methods used for AM components. There will be major improvements in AM equipment both at small and yet realized industrial scales, simplification of its workflow, and development of data-driven quality control systems enabling on-demand production. The automotive and consumer sectors may ultimately be AM's largest markets many years from now.

AM also presents issues that must be considered by policymakers. AM, in concert with 3D metrology techniques, may simplify the workflow of reverse-engineering components. Home use of the technology compels policymakers to differentiate intellectual property rights where the geometry (and its digital representation) of parts produced by Original Equipment Manufacturers are concerned. Central to this discussion are issues related to the Right-to-Repair movement, as well as the scope of current copyright protection regimes, including the Digital Millennium Copyright Act. The same concerns apply not only for personal uses of AM, but for industrial or national uses where the technology may be used for subversive purposes related to corporate espionage or digital warfighting.

Thus, to fully realize the potential of AM, we propose that governing bodies consider the following recommendations:

1. Invest in the full spectrum of basic AM research to applied commercialization.
2. Support small- and medium-sized enterprises to develop AM capacity and expertise.
3. Foster high-quality, workforce-oriented training programs at all levels.
4. Accelerate approaches to open innovation with AM as a fulcrum.
5. Understand and proactively combat the prospective risks of intellectual property piracy, counterfeiting, and reverse engineering.
6. Define through legislation the ownership of digital information and specify the boundaries between consumer and manufacturer rights for product repair.

The text below supports these recommendations, beginning with a discussion introducing AM and benchmarking the technology's current status. We then articulate the barriers to AM's adoption. We summarize the implications of AM technologies in driving consumer and industrial value, providing context for why the described challenges must be overcome. Last, we reveal the potential growth trajectories of AM with several industry-specific examples and conclude with a thorough discussion of the policy recommendations.

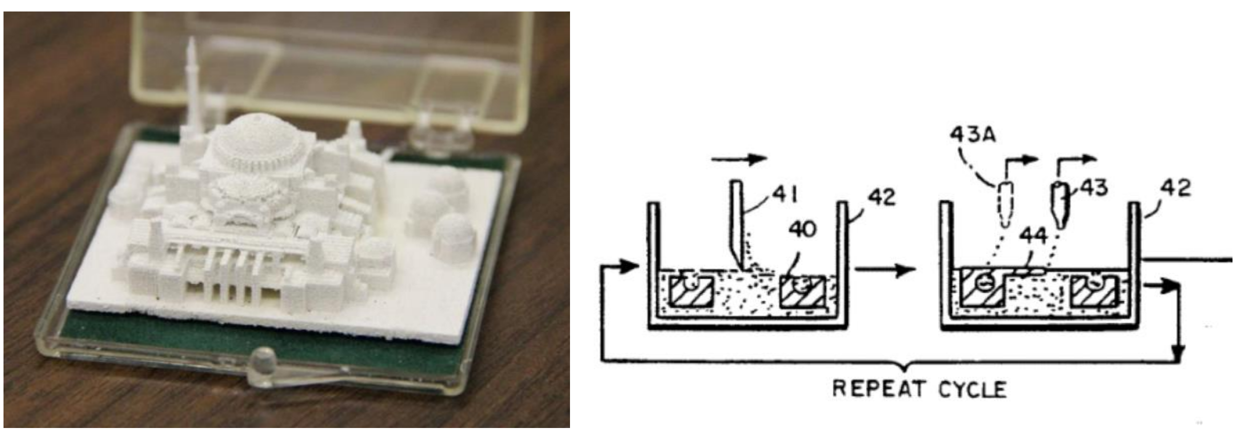
Introduction to Additive Manufacturing

BACKGROUND AND HISTORY

Additive manufacturing (AM)[1] has the potential to transform how products are developed and realized. AM, by and large, can eliminate the need for product-specific tooling and can build highly complex geometries that consolidate multiple parts, are more material-efficient, and combine materials in previously impossible ways. The use of AM for on-demand production can reduce cost and lead time and has the potential to enable the consolidation of supply chains.

The seeds for AM's present industrial growth were first planted in the 1980s and 1990s via the invention of many technologies and through the gradual yet persistent adoption of AM systems for rapid prototyping across industries. Many early inventors of such systems commercialized their ideas into companies, including Stratasys (polymer extrusion) and 3D Systems (photopolymerization), which now command significant market share within the AM industry. Though the earliest AM technologies produced often fragile, coarse objects (Figure 1), cumulative advances in materials, hardware, and software—the fundamental ingredients of 3D printing and, more broadly, industrial automation—have readied AM for mainstream adoption. The landscape of industrial stakeholders and industry participants has also blossomed, especially due to the expiration of several key patents in the past 15 years. Now, firms are increasingly interested in digitally driven business and production models that operate more efficiently—requiring less physical infrastructure, human labor, and other resources—to produce more a more flexible and responsive catalog of parts and products in response to changing consumer preferences and supply-chain risks.

Figure 1. Small Replica of the Hagia Sophia, Printed Using an Early MIT 3D Printing System, and Schematic of the Printing Process which is Now Referred to as Binder Jetting.



Source: Photo by A. John Hart. Schematic from US Patent 3,204,055A.

Desktop 3D printers have also attracted interest as consumer products for home use. Inspired by the twin prongs of the burgeoning "maker" movement and increasingly affordable and accessible desktop printing equipment, excited hobbyists envisioned and espoused a manufacturing revolution. In the vision of the times, reflected in documentaries such as 2014's *Print the Legend*, so-called prosumers (a portmanteau of "producer" and "consumer") would be enabled to engage materially with the products they consume through augmentation, modification, and maintenance performed using components printed at home. Some speculated that printers could be used like the "replicator" in the popular TV series *Star Trek,* which can create any product instantaneously (MakerBot's third-generation printer was actually named the Replicator). At one point, *The Economist* mused over whether AM could be used to replicate a Stradivarius. In the era's most far-reaching aspirations, a digitally connected swarm of home devices was envisioned, as ubiquitous as microwave ovens, that could provide manufacturing capacity for the rapid fabrication of nearly limitless geometries. Less optimistically, concern rapidly grew, and later faded, over the prospect of criminal actors producing untraceable 3D-printed firearms at home. Similar concerns were raised about reverse engineering devices for the purposes of corporate espionage or asymmetric warfare. In practice, none of these predictions were yet fully accurate, but the ethos of each of these ideations—that AM is uniquely positioned to radically alter the methods that individuals and corporations use to engage with customers, design components, and fabricate them—remains fundamental to AM's growth in industry. It is therefore instrumental to the realization of flexible and robust digital production infrastructures.

AM technologies are being strategically deployed across the manufacturing firm and product lifecycle to improve product and business process performance. Moreover, AM is also important for its interrelationship with other technologies within the "Industry 4.0" umbrella, which colloquially refers to a series of digitally enabled assistive manufacturing technologies that range from robotics to computation. These technologies blend physical production activities with a connected digital supporting infrastructure to create a cyber-physical system; within these systems, the infrastructure is considered configurable to various tasks, rather than dedicated to individual, predefined production roles. Industry 4.0 seeks to leverage this intelligence to analyze and optimize factory operations, improving quality and enabling production flexibility while reducing risk. Insofar as AM requires only enough process hardware and 3D geometry data to produce a part (and, importantly, does not require part-specific tooling), it is intrinsically flexible in terms of what components a system produces.

AM is therefore considered to be a cornerstone of Industry 4.0, where digital data is secured and produced remotely, just in time, using sophisticated AM systems. AM systems will monitor the production process in real time and provide data and insights that allow users to identify and eliminate waste or failure. Distributed production (production of finished components at various locations) will be enabled by keeping this data in a closed loop—allowing adaptation to a variety of input materials, machine capabilities, and other disturbances while guaranteeing quality control. When firms are unbound by the economic requirements to produce large quantities of a fixed design—a necessity for many parts, and therefore products, that require dedicated tooling—they may explore new models of integrating customer preferences and data to define new value dimensions such as by providing customizations to individuals and/or groups of users.

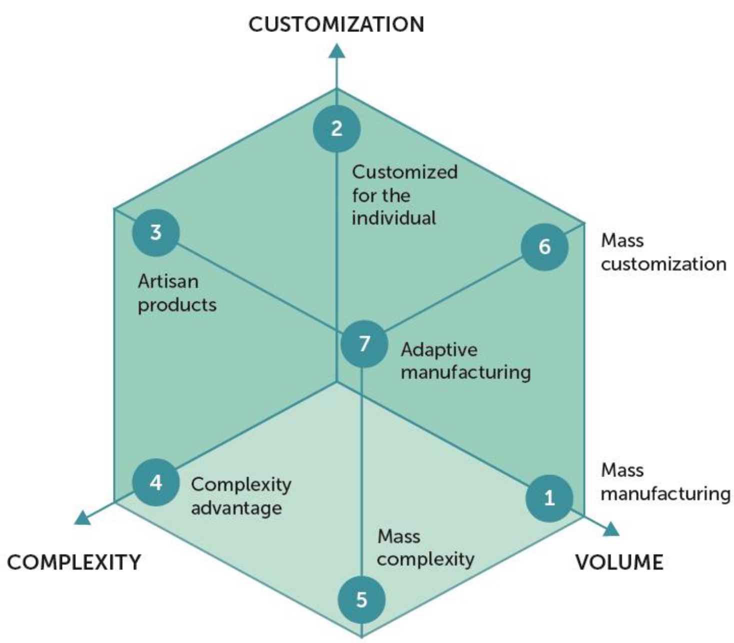
Figure 2. Selected Industrial and Consumer Applications of AM

(a) Fuel nozzle for aircraft engines made by laser powder bed fusion (GE), printed as a single piece; (b) Metal hip implant component made by laser powder bed fusion, with three-dimensional porous surface that aids bone integration; (c) FAA-certified structural galley bracket for Boeing 787 (Boeing); (d) Futurecraft 4D athletic running shoes, with printed midsole (adidas/Carbon); (e) Customized orthodontic retainer formed using a 3D printed tool (Align Technologies); (f) Faucet with internal channels for water flow (American Standard); (g) In-ear hearing aids, printed-to-form based on patient ear canal geometry (Widex); (h) Performance mountain bike with custom-printed metal joints connecting carbon fiber tubes (Robot Bike/Renishaw); (i) Rendering of a modular figurine face, printed via material jetting, used for stop-motion capture film production (Laika); (j) Mascara brush with polymer tip produced by selective laser sintering (Chanel); (k) Textured automobile dashboard inlay, fabricated to-order (BMW); (l) Diamond engagement ring made via lost-wax casting with a 3D-printed mold (Nervous System); (m) Fast-release pill produced made by binder jetting (Apredia); and (n) figurines of South Park characters, made by binder jetting (Source3 by Amazon.com).

While this transformative vision is in its infancy today, commercial examples of AM (Figure 2) range from basic consumer applications—including Hero Forge's web-based configurator for customized, 3D-printed miniatures—to industrial contexts, where aerospace engine manufacturer GE has put more than 30,000 additively manufactured engine components in the skies. Arguably one of the most compelling examples of AM's potential is embodied by Align Technologies, which produces patient-specific orthodontic retainers.

Align Technologies uses a fully digitally integrated production workflow, beginning with a scan of the patient's mouth, followed by digital modification of the scan data to describe the desired final tooth alignment. These endpoints are then translated into a series of rehabilitative retainers that gradually exert directed force to realign the patient's teeth into the desired arrangement; these retainers are produced by 3D printing a polymer mold, which is then used to form the polymer retainer. Align Technologies produces millions of customized retainers for patients around the world each year, realizing mass customization at a scale unthinkable were it not for AM. Firms such as Mercedes-Daimler are using AM technologies for on-demand fulfillment of spare parts for certain legacy vehicles, employing a minimal-overhead practice of "digital warehousing," which replaces physical spare parts and associated production tools with 3D data stored in the cloud—a system only possible thanks to AM. This practice is also being deployed, with appropriate certification protocols, in the aviation, defense, and construction industries; it is particularly useful for heavy equipment and in remote locations. Taken in total, these examples speak to what Conner (2014) calls "complete manufacturing freedom"—a future state where a firm's capabilities enable it to realize any combination of product complexity, customization, and volume (Figure 3).

Figure 3. Three Axes of Manufacturing System Capability



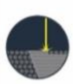
Source: Adapted from Conner (2014)

DEFINING ADDITIVE MANUFACTURING PROCESSES

AM encompasses a broad library of forming processes, which can process a wide variety of materials, and produce components from small to large. The American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) have spearheaded efforts to develop standards for

AM technology. ASTM defines AM as a "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies." This definition encompasses processes that vary with regard to their mechanism of fusion, material compatibility, build rate (i.e., volume built over time) and dimensional resolution (i.e., beam width or layer thickness), energy demands, and other attributes. AM processes range significantly in their capabilities and can be used today to form high-precision polymer components at the micro- and nanoscales as well as structural metal or cementitious components with dimensions of many meters or more. The ASTM Committee F42 on Additive Manufacturing Technologies further classifies AM processes within seven categories (Table 1), though there are myriad hybrid processes that elude precise classification. The lattter include emergent technologies that combine AM with machining, e.g., to produce large, highly complex metal parts with precision features, and those that combine multiple characteristics of different AM processes (e.g., extrusion of a ultraviolet-curable photopolymer gel).

Table 1. ASTM/ISO 52900:2015(E) Additive Manufacturing Process Definitions

PROCESS NAME	ASTM/ISO 52900:2015(E) DEFINITION	MOST COMMON MATERIALS
Binder Jetting (BJ) 	process in which a liquid bonding agent is selectively deposited to join powder materials	Metals, ceramics, sand
Directed Energy Deposition (DED) 	process in which focused thermal energy is used to fuse materials by melting as they are being deposited	Metals
Material Extrusion (FDM/FFF) 	process in which material is selectively dispensed through a nozzle or orifice	Polymers, composites, metals, organics, cementitious
Material Jetting (MJ) 	process in which droplets of build material are selectively deposited	Polymers, wax
Powder Bed Fusion (PBF) 	process in which thermal energy selectively fuses regions of a powder bed	Polymers, metals
Sheet Lamination (LOM) 	process in which sheets of material are bonded to form a part	Composites, metals, paper
Vat Photopolymerization (SLA) 	process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization	Polymers

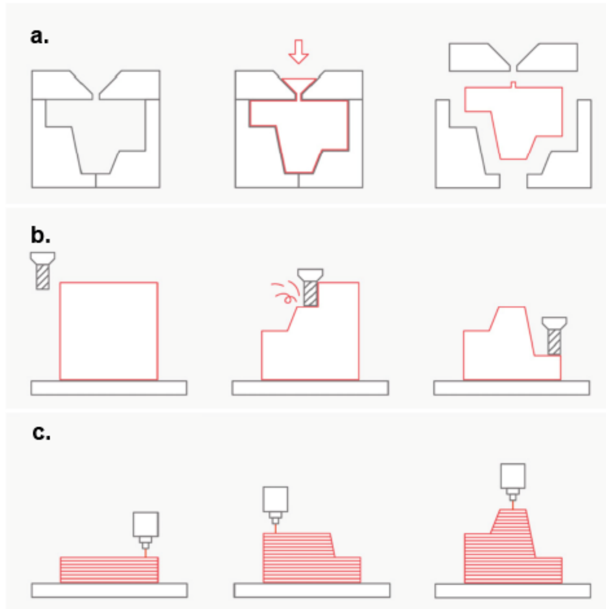
Note: Each process is associated with a representative graphic (courtesy of MITxPRO) that illustrates how the material is formed for each process.

Moreover, AM processes are unified through their workflow approach, which begins with digital modeling and data preparation. After a digital 3D model of a component is prepared, AM begins by “slicing” the geometry into a series of cross sections. These cross sections are formed sequentially in stacked layers during the printing step. After printing is performed, the parts are removed and cleaned of artifacts or vestigial supporting material (which is often necessary for the 3D shape to be created without tooling), and optionally treated further to improve the component’s properties or surface finish. Thus, with AM, the material exists first in unfused feedstock format (as a powder, spool, pellet, or other mode) and is then selectively deposited by the system to create a near-net shape geometry, which is then finished using various secondary processes. Recognizing that even after forming the 3D shape, multiple steps are often necessary to create the finished component, one may denote the machine that forms the part as the “3D printer” and the end-to-end process as AM.

When a smooth surface finish is desired, for example, an AM component may be polished or machined after its production. When strong mechanical properties are required of metal AM components, parts may undergo heat treatment procedures to consolidate the formed material and eliminate internal voids. AM therefore requires a robust production workflow from design to finishing to be used to realize final components. Moreover, in most cases, AM makes parts and not products; most products comprise many parts made by different processes.

Yet, AM is unlike manufacturing methods (e.g., machining or turning) that begin with a solid workpiece of material and form the finished component by a series of subtractive removal steps, similar to a carving or sculpting process (Figure 4). It is also fundamentally different from formative manufacturing methods (e.g., molding or casting) in which material is injected into a negative pattern of the part’s geometry, filling the empty space within the mold with the component material as it injected. In subtractive manufacturing, complex fixturing may be required and, at minimum, the cost and time needed to form components is directly related to the complexity of the form and the amount of material removed. In contrast, AM process are generally cost-insensitive to variations in component complexity, as we will discuss later.

Figure 4. Contrasting Conventional to Additive Manufacturing



Adapted from *The 3D Printing Handbook* (3D Hubs, 2017). (a) Formative manufacturing, where a component is formed via molding a predefined shape. (b) Subtractive manufacturing, where a component is formed via the removal of material from a stock workpiece. (c) Additive manufacturing, where a component is formed by selective, layer-wise material deposition.

Moreover, AM offers, relative to other manufacturing methods, significantly greater freedom to create a variety of shapes. In subtractive manufacturing, for example, geometries are bound by rules governing the accessibility of cutting tools to remove material. Typically, holes must be straight, and it's not possible to create enclosed internal cavities. In formative manufacturing, rules governing the flow of molten material as it navigates the mold cavity limit the complexity of components produced. Though limitations do exist for AM processes, AM allows for much greater geometric complexity than other conventional forming approaches. Computational design approaches, commercialized through topology optimization and generative design software, allow engineers to design shape-optimized components tuned to meet an application's functional requirements (Figure 5). Likewise, the use of lattice structures has been aggressively explored in AM as a means of preserving macrostructural properties of components while minimizing their weight.

Figure 5. This rendering of a generative design workflow contrasts a conventionally machined bracket (far left) with iterative improvements in material placement resulting in a shape-optimized, additively manufacturing bracket (far right).

Source: GE

These two characteristics—AM's intrinsic flexibility and its inherent ability to realize complex geometries — are what justify AM's application across an impressive breadth of industrial use-cases. Taken in total, AM is therefore best understood as a technological substrate upon which ideas can be realized at comparatively shorter lead times and lower costs by eliminating the secondary requirement to fabricate tooling or to associate production activities to a dedicated facility, as well as the technology's intrinsic expansion of the accessible design space. Currently, components made by AM are used in nearly every environment and industry—from simple consumer products to performance components for aerospace or deep-sea exploration to devices implanted into the human body. Though AM is unlikely to replace the principal manufacturing approaches used for many established products, its adoption within manufacturing environments has transformative implications for how manufacturing firms introduce new products to the marketplace. From first concept (e.g., rapid prototyping) to end of life (e.g., on-demand spare part production), AM will unlock new efficiencies and possibilities in the manufacturing of nearly all finished goods. Even when conventional strategies are chosen for component manufacturing, the use of AM for everything from simple fixturing (Figure 6) to the creation of worker personal protective equipment may improve component quality, increase worker ergonomic safety, and minimize wasted time or resources.

Figure 6. AM-Produced Fixtures and Worker Assistive Tools

LEFT: Alignment jig for Nameplate Assembly (Volkswagen/Ultimaker). RIGHT: Thumb-cot for structural ergonomic reinforcement for automotive assembly task (BMW).

In recognition of these prospective advantages, over the past few decades, the AM industry has grown significantly in size and application scope. One measure of the technology's market penetration is reflected in the annual sales of machines and services, indexed each year by the firm Wohlers Associates. Its 2020 report shows that the AM sector grew by 21.2 percent in 2019—reaching $11.87 billion in materials and services. This growth rate is comparable to the entire industry's 30-year compound annual growth rate of approximately 26 percent, reflecting strong industrial uptake of AM systems. Moreover, the United States has established itself as a global leader in AM technology. The plurality of AM system device manufacturers (approximately 22 percent) are headquartered in the United States, and between 2019 and 2020 an additional 14 U.S. firms entered the marketplace. The U.S. is notably home to many of the largest AM system manufacturers; in 2019, three U.S.-based firms alone accounted for approximately 40 percent of global industrial system sales (classified as a system greater than $5,000), per the Wohlers report. Since 1988, the United States has accounted for 42.5 percent of all AM system sales, including both industrial and desktop (less than $5,000) systems. Finally, these systems are not only sold by U.S. firms in large quantities but are installed in the United States in equally large numbers. In 2019, the great plurality of systems (34.4 percent) were installed in the United States. The second largest user, China, accounted for just 10.8 percent of installations.

In 2019, production of end-use parts represented roughly 31 percent of total AM applications surveyed, eclipsing the 24.6 percent dedicated to the production of functional prototypes; therefore, we can safely conclude that AM has finally transitioned from being exclusively a rapid prototyping service to one with mainstream uses that meet qualification standards, albeit with some considerable limitations that we will describe in the following sections.

Still, AM represents a slim fraction of total manufacturing commercial activity, which totaled approximately $13.8 trillion in 2019, the most recent year for which World Bank data is available. Yet, using commercial activity as a proxy for industry growth understates the technology's significance; 2018 and 2019 marked the crowning of the first three AM "unicorn" start-ups—Desktop Metal, Carbon, and Formlabs—and many industrial users have made significant commitments to AM research and production infrastructure (e.g., in June 2020, BMW unveiled a dedicated AM campus). Several high-profile mergers and acquisitions, such as General Electric's $1.4 billion acquisition of system providers Arcam (including materials subsidiary Advanced Powders and Coatings) and Concept Laser in 2016, also indicate industry growth far exceeding sales and service totals.

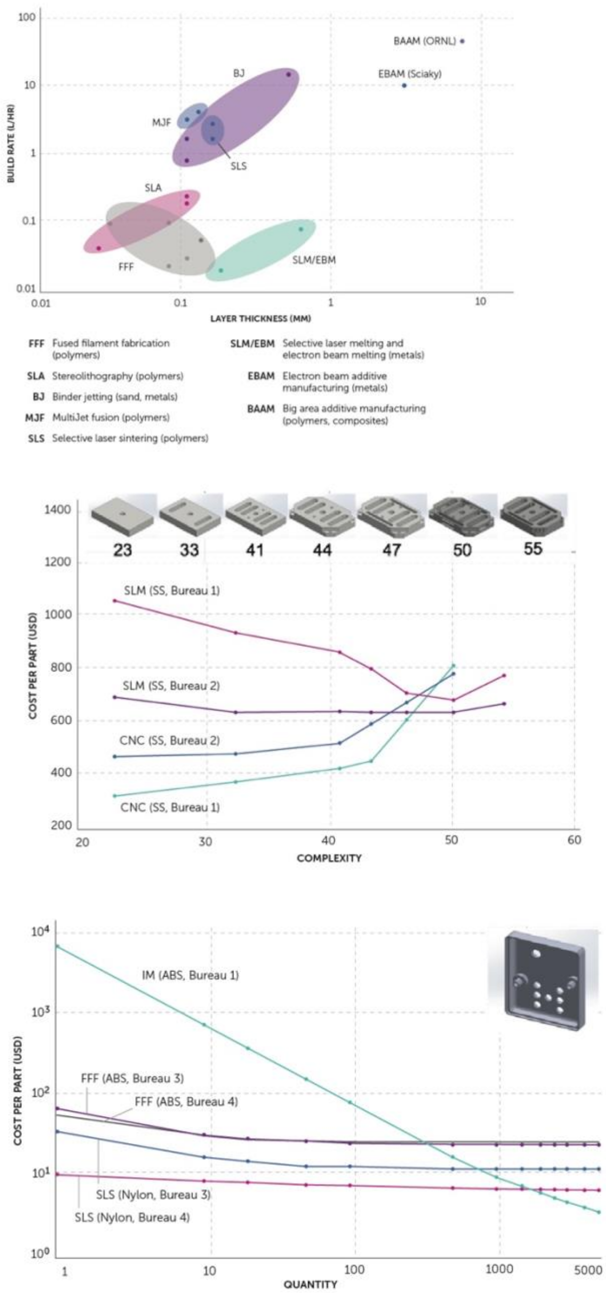
Status of AM Technology

PROCESS PERFORMANCE METRICS

Several metrics can be used to assess the current status of AM processes. *Build rate* represents the average volumetric throughput of an AM system, i.e., the volume of material formed per unit time. This rate, which varies depending on process, material, and geometry, is an approximate benchmark of the system's productivity. *Resolution* defines the processes' minimum feature size and may be approximated by the thickness of the smallest formable layer. *Build volume* reflects the size of the production chamber within the AM system. This parameter determines the maximum part dimensions that the system can produce and, in tandem with the system's *build rate*, governs the suitability of a particular AM system when a specific part is assessed for production.

In Figure 7a, we summarize the approximate build rate and resolution of selected AM processes based on the specifications of professional-grade equipment. This reveals that most AM processes have a low overall build rate (approximately 0.01-1 liter/hour) and generally low resolution (approximately 0.1 mm); these results are inferior to most molding and machining processes for similar materials. Importantly, the comparatively limited speed of AM processes currently throttles the technology's industrial adoption. For large-volume applications (i.e., many units), AM processes may be unacceptably sluggish to meet production targets. Moreover, due to generally expensive system costs (Figure 8), large capital investments in machinery as well as associated, fixed, per-job costs for labor must be amortized over comparatively fewer produced goods; this significantly elevates the price per component or unit of formed material. This relatively high cost hinders AM's adoption for applications where large product volumes are required. As Baumers and colleagues (2016) conclude, "High specific costs … are identified as a central impediment to more widespread technology adoption of … additive systems. …The research demonstrates differing levels of system productivity, suggesting that the observed deposition rates are not sufficient for the adoption of [several metal AM printing methods] in high volume manufacturing applications."

Figure 7. Performance and Cost Metrics of AM Processes



(a) Build rate versus resolution (layer thickness here is used as a proxy) for each mainstream AM process. (b) Cost of component production at various orders of complexity contrasting computer numeric control machining with selective laser melting. (c) Cost of component production at various order quantities contrasting polymer AM processes with injection molding. Data for (a) were drawn from literature and machine manufacturers; data for (b) and (c) were drawn from industrial service providers with quotation services.

However, AM's potential cost premium does not universally preclude AM from finding an industrial home. Many early uses of AM focused on low-volume applications where customers were willing to pay significant premiums for higher-performing products (e.g., weight-optimized components for aerospace, performance automotive applications, and medical devices that could improve patient outcomes or treatment efficiency). Yet, improving AM process performance goes hand in hand with expanding the application space.

Recently, for AM using polymers, major improvements in build rate have been achieved without sacrificing resolution, such as by high-speed sintering (e.g., HP's multi-jet fusion technology) and photopolymerization (e.g., Carbon's digital light synthesis technology). As the technology matures, higher-volume applications of AM continue to be demonstrated. In 2018, beauty and fashion supplier Chanel, for example, announced the production of a novel mascara brush with improved performance; the shaft of the brush is entirely 3D printed using a laser powder-bed fusion process in quantities exceeding 1 million units per month. Emerging technologies for metal AM—including laser-based methods and those based on solid-state consolidation of powders—are also achieving higher throughput.

It is often said that AM provides "complexity for free" or "complexity for the same cost as simplicity," meaning that the addition of complex features does not inherently increase the part's production cost when AM is used (Lipson and Kurman, 2013). This is because with AM processes, *ceteris paribus,* the location and quantity of distinct features generally does not considerably increase cost. In some cases, more complex features can even reduce the overall mass of the component. Since AM processes are generally material-efficient, reduced mass corresponds to reduced cost through reduced material consumption and improved per-part cycle time. In 2017, we researched (via service bureaus) the cost of manufacturing a single stainless steel part[2] (Figure 7b) with increasing geometric complexity.[3] For this example, we compared quotes from two established AM service bureaus for the production of the same part using a subtractive computer numeric control (CNC) machining process and a laser powder-bed fusion AM process (selective laser melting, SLM). The results illustrate that, while the cost of CNC machining increases with complexity, the cost of making the same (single) part by AM decreases or remains relatively invariant with complexity. The downward trend for AM in the case of one service bureau is likely due to reduced material usage and build time. The most complex test case, where the part has enclosed internal cavities, cannot be made by CNC machining of a single piece. The cost premium for SLM is significant for simple geometries—at least two to four times that of CNC machining, without considering surface finishing or the machining needed to meet dimensional tolerances.[4] However, the costs of SLM and CNC are comparable for parts of moderate to high geometric complexity, and for such cases AM is likely to overtake machining as feedstock costs drop and machine performance continues to increase.

For polymers (Figure 7c), AM provides a nearly flat cost-quantity relationship, overcoming the fixed-cost barrier for tooling required to set up an injection molding process. Here, for an exemplary plastic housing,[5] the break-even point between AM by fused filament fabrication (FFF) and injection molding of a common thermoplastic polymer (acrylonitrile butadiene styrene, ABS) is approximately 300 units, and for selective laser sintering (SLS) of nylon it is approximately 1,000 units. The precise cost-volume trend for AM will be influenced by the utilization of the AM machine(s) and post-processing operations, among other factors.

In Figure 8 we summarize the approximate cost and build volume of a separate subset of selected AM systems. This comparison demonstrates a simple relationship in which, for the most part, build volume is directly associated with greater capital cost. This is an intuitive relationship whereby the cost of increasing build volume requires commensurate increases in associated hardware systems, thus elevating the total cost for a given system.

In tandem with the previously discussed dynamic, where AM is preferentially competitive with conventional manufacturing for lower-volume components, AM processes are typically most efficient in producing small, complex, high-value components that can be efficiently arranged within a given build volume (e.g., as shown in Figure 9). At present, process planning for the ideal arrangement of components for optimizing part quality and production efficiency is largely derived through per-application trial and error. However, as the industry matures, best practices for part production will be codified into dedicated "build preparation" software tools, making AM more accessible for a wider range of production environments; already these tools incorporate user-friendly features for optimizing component orientation and part layout.

Figure 8. A Comparison of Build Volume and Machine Cost for Various Commercial AM Systems

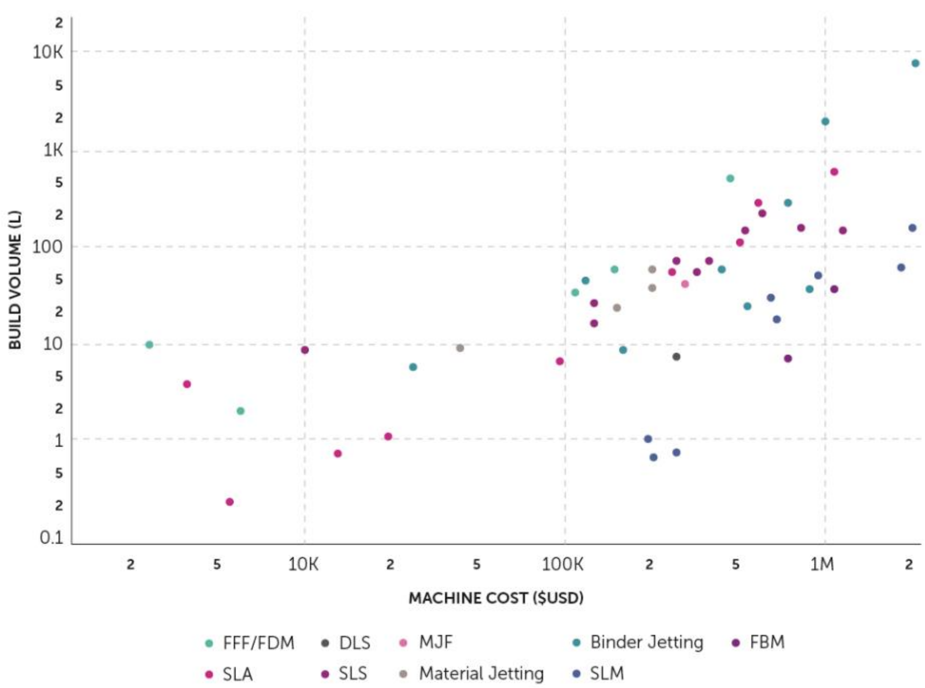
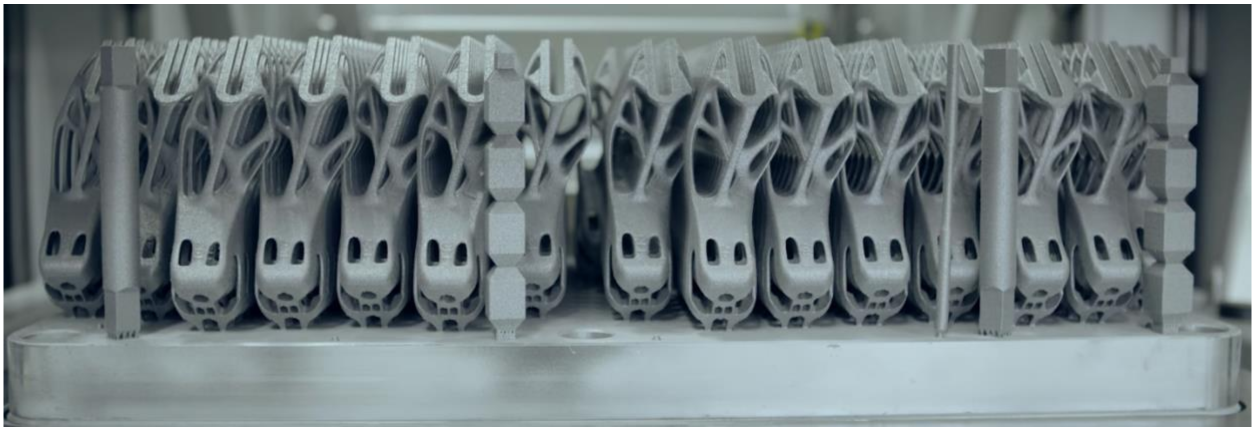


Figure 9. Hinge brackets for the BMW i8 Roadster are arrayed on a build platform after printing has concluded.



Source: BMW

AM processes for large parts are also gaining significant market traction. These include binder jetting for sand tooling (ExOne, Viridis3D), large-bead extrusion of fiber-filled thermoplastics (ORNL's BAAM process), concrete extrusion for remote construction (ApisCor), and electron-beam AM of metals by wire-feed deposition (Sciaky). AM of larger parts poses technical challenges (e.g., maintaining accuracy of machine motion or managing thermal histories when comparatively larger masses of deposited material are used), but surmounting these obstacles will enable AM production of large components for broad applications, including those in the construction, infrastructure, energy, and rail transportation industries.

TECHNICAL CHALLENGES TO THE ADOPTION OF AM

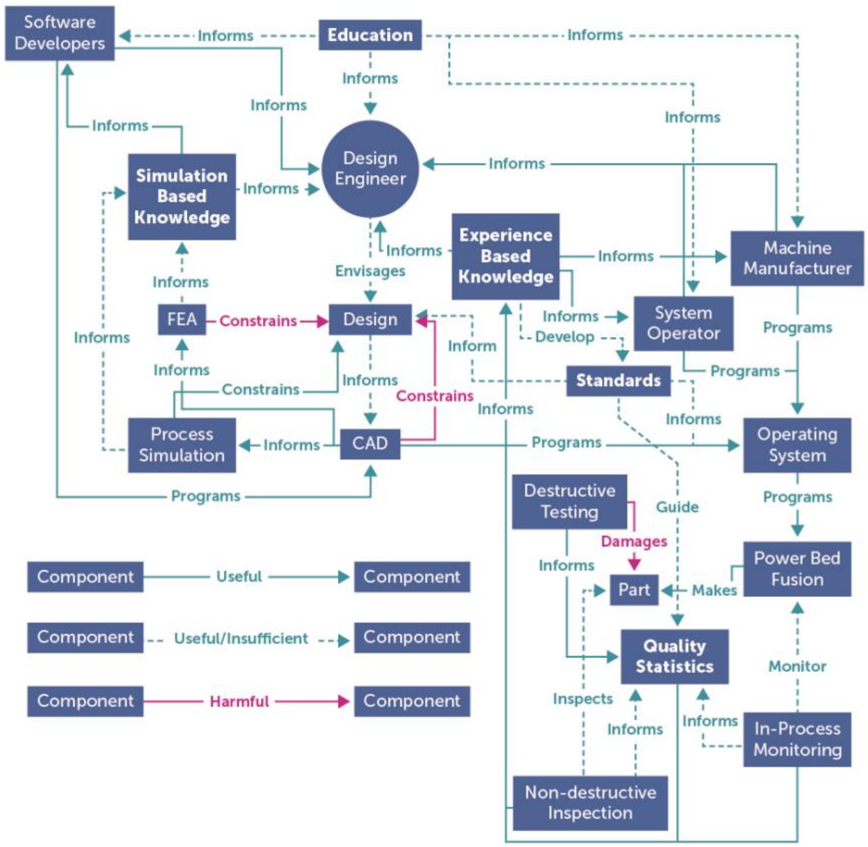
Beyond economic challenges, AM processes also face a series of fundamental technological challenges related to the properties of produced components. In subtractive manufacturing, for example, the properties of finished components are defined by the bulk-forming process used to prepare the workpiece prior to the subtractive operation. These properties are well understood, are derived directly from the material's established microstructure, and generally do not change as a result of the material removal process (though additional treatment steps may be performed to improve surface finish or other characteristics). In additive processes, however, the component's microstructural characteristics are defined by a combination of material formulation and processing conditions (e.g., the density of deposited energy within a defined volume). Process parameters (e.g., the exposure time for an energy source) must also be modified depending on the specific geometric characteristics of the component as well as its orientation during the build. Additionally, secondary processes (e.g., support removal or thermal stress relief) may be necessary depending on the AM process utilized, and these may further modify the component's properties. The combinatorics of these various elements creates significant challenges in the early realization of printed components, since identifying the correct recipe often requires significant trial-and-error experimentation. Moreover, even when an approach is codified, the repeatability of the AM process from site to site or from machine to machine may be uncertain due to variations in material characteristics between batches or in processing conditions within the machine or facility. Finally, the library of materials available for use in AM processes is somewhat constrained by the forming physics of the process employed; for example, in melting-based metal AM systems, materials must be resilient to the rapid heating and cooling of the selective fusion process.

In total, technical challenges raise significant issues for the introduction of AM applications within firms, especially those with limited working capital. Since these challenges induce uncertainty and thus introduce cost and schedule hazards, small and medium enterprises are not always willing to take the risk of exploring an AM application, which requires a large up-front investment in development to qualify the process and product for volume production. These firms are less able to compete with larger entities that may have stronger in-house engineering talent or the ability to engage third parties to accelerate development. However, large firms have also found AM technologically or economically unfeasible, choosing to curtail their AM activities in favor of other initiatives.

Standardization bodies have played—and will continue to play—an invaluable role in the development of standard practices for manufacturing firms seeking to introduce AM technologies into the factory environment. In 2018, AmericaMakes and the American National Standards Institute released a roadmap for the tiered generation of AM standards. The ASTM/ISO F42 Committee, for example, has dedicated technical subcommittees focused on Test Methods (F42.01), Design (F42.04), and so forth. As these standards are developed, AM equipment manufacturers are filling the knowledge-to-practice gap by commercializing application development consulting services (e.g., GE AddWorks or EOS Additive Minds).

Technical and economic challenges are amplified by the generally tight labor market for experienced AM professionals. Though the process has an established history of industrial use, its adoption specifically for series production is relatively novel within the past decade. Moreover, the industry's rapid pace of development has made professional upskilling a persistent need, rather than a one-time training investment. As Thomas-Seale (2018) and others have shown, education and process knowledge are prerequisites to mastery of all aspects of the AM production workflow (Figure 10). As a result of labor dynamics, and in part due to the trial-and-error development approach common to AM, many AM-focused business units find themselves relying on highly qualified workers to perform tasks they believe could be done by less skilled employees.

Figure 10. Logic Map Illustrating the Primacy of Knowledge and Education in the Additive Manufacturing Workflow



Source: Adapted from L.E.J. Thomas-Seale et al, 2019.

In practice, the aforementioned economic and technical challenges can be overcome by an experienced workforce, which can reduce development time and cost through applied understanding of the AM process. BMW, for example, is producing tens of thousands of aluminum components for its i8 Roadster at a cost-competitive price point compared to die casting (Figure 9). The parts shown in the figure require very minimal manual labor to finish post-production due to their careful design and layout inside the build chamber; they are removed from the build platform by hand, rather than via a mechanically assisted method (e.g., a band saw or handheld cutting tool), saving significant time and cost. The parts are then finished using an inexpensive bulk finishing process. In between the parts, small columns of different geometries are visible in the figure. Some of these columns comprise stacked vials, each of which captures small quantities of powder corresponding to a cluster of layers, creating a physical artefact that can be stored and examined in case of defect or part failure. Others are rods used for validating the strength of the printed bracket components. This application demonstrates that a tightly interconnected understanding of the relationships between a component's design, its production strategy, and its qualification methods can be leveraged to realize compelling value-added applications of AM at significant scale.

THE ADDITIVE MANUFACTURING WORKFORCE

AM-dedicated education is being deployed at all levels of instruction. Desktop hobbyist-style 3D printers are increasingly being used in K-12 educational settings to augment lecture-based instruction through laboratory exercises. At the university level, many institutions have "maker spaces" or other accessible 3D printing resources. Pennsylvania State University offers a master's degree in additive manufacturing and design, and many universities, including MIT, Purdue, and the University of Illinois at Urbana-Champaign, offer professionally focused workforce training programs. Professional societies offer workforce-level training as well: ASTM and AmericaMakes have partnered with Auburn University on an AM Center of Excellence that will produce workforce materials (trainings or roadmaps for third-party training initiatives). In Europe, the European Welding Federation is tasked with developing curriculum standards for job-specific worker qualification programs.

Despite a growing body of professional training initiatives for AM, there is evidence that such initiatives may be insufficient to address the shortage of qualified professionals. A 2018 study cosponsored by Deloitte and The Manufacturing Institute concluded that there may be a total of 2.4 million unfilled manufacturing jobs in the United States between 2018 and 2035 and that the great majority of manufacturing executives (89 percent) perceive a talent shortage in U.S. manufacturing. This perception is corroborated by long-term data from the Bureau of Labor Statistics.[6] Since 2012, manufacturing organizations have increasingly been unable to hire skilled laborers for open positions. The hires-to-openings ratio (Table 2) describes the relative ability of industry sectors to fill available positions; a ratio exceeding 1 indicates that more hires are made than there are open positions, indicating that the job market is sufficiently saturated with qualified workers for those roles. When the ratio drops beneath 1, it indicates that there are insufficient qualified workers available to perform unfilled roles. While this is a simplistic and reductive interpretation (there are many possible confounding effects, such as inefficiencies in hiring practices, for example), the hires-to-openings ratio is a useful heuristic indicator of the general alignment between an industry's workforce demands and the availability of labor. Over the past several years, manufacturing hiring has consistently fallen well short of meeting available openings; in 2017, for example, 15 percent of openings were unfilled.

Table 2. Hires-to-Openings Ratio in Manufacturing, 2007-2017

INDUSTRY	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
MANUFACTURING	1.12	1.27	1.91	1.46	1.11	**0.91**	**0.92**	**0.90**	**0.86**	**0.82**	**0.85**

Moreover, more workers are leaving the manufacturing sector than ever before. Between 2015 and 2018, for example, the percentage of the total manufacturing workforce that left the industry increased each year annually from 25.6 percent (2015) to 32.5 percent (2018). In 2019, the last year for which complete data is available, 31.3 percent of the manufacturing workforce left the industry. While increased worker turnover generally characterizes most economic activity for this period, few sectors have had turnover of commensurate magnitude to the manufacturing sector. There are many reasons for increased worker turnover (the Deloitte/TMI study, for example, points to retiring baby boomers), but one is the displacement of less skilled workers. For example, one Georgetown University study notes that the percentage of "good jobs" allocated to manufacturing workers without a bachelor's degree decreased by 44 percent between 1991 and 2016. Now more than ever, workers with postsecondary education are consuming a larger fraction of all manufacturing jobs (including production roles, which have typically been dominated by less skilled workers). This trend would not be intrinsically problematic from a workforce-supply perspective if it were not coupled to the decreasing attractiveness of manufacturing work to new college graduates reported in the same Deloitte/TMI study.

We consider that AM may only accelerate or amplify these dynamics. Though the complete workflow for AM is not entirely distinct from conventional manufacturing, many activities require specific skillsets in the monitoring and operation of AM equipment, the use of AM-specific production software, and in the characterization of printed components. Our research, conducted with a large industrial user of various AM processes for energy applications, investigated the influence of AM on the sequencing and efficiency of product development activities when AM is chosen as the principal production method. One of the main findings related to the cooperation between various functional roles; when implementing AM initiatives, all personnel involved in the design and production of a new AM-made component must cooperate on a foundation of shared knowledge and understanding because production software, component design, and manufacturing strategy and execution are strongly interrelated. In other words, an increased intellectual burden, requiring domain-specific skills and knowledge, is placed on workers across functional roles. Our case study partners deemed the cooperative exercise of this knowledge essential insofar as AM processes and applications are generally nascent for the primary production of complex industrial goods, and thus development work—the act of defining standard operating procedures, design rules, and so forth—proceeded in parallel to the exploration of a new AM product introduction. As a result, one supervisor indicated that the firm relied on explicitly "overly qualified" workers—opting to hire PhD-level employees despite their belief that lower-skilled workers with the appropriate domain-specific knowledge would be satisfactory (although they might not have existed).

Practically, AM production skillsets can arguably be acquired by workers with less education (e.g., those without a bachelor's degree). For example, AM system operators and technicians need only understand and execute a production workflow prepared by others. Operators load predefined files into the machine and extract parts once the print operation has finished. They may also perform simple routine maintenance (such as cleaning powder residue off critical surfaces and optical elements), which requires only machine-specific knowledge. In the same way that a CNC machinist may execute a toolpath prepared by a manufacturing engineer, an AM technician may be simply the physical executor of a workflow rather than its designer. These skills are likely transferable from other skillsets related to machine maintenance and supervision (e.g., attention to detail, the ability to follow a discrete and precise workflow, etc.). In addition, many finishing operations for AM components today are manual. Support removal may be done using simple mechanical methods such as hand tools or a band saw, and surface finishing may be completed using a variety of easily learned techniques (such as sanding, sand-blasting, painting, and so forth). These skills are not unique to AM, and laborers with these skills can easily convert from a conventional production environment to an additive one.

Importantly, low-skilled workers need not be relegated only to such routine tasks. At present, choices made in the preparation of a print—e.g., how parts will be arranged within a build volume, and what parameters the machine will utilize during its construction—significantly influence the component's mechanical properties and the efficiency of the production workflow; hence why technically advanced workers are employed to perform these tasks. This *status quo* is a byproduct of the nascency of AM, where trial-and-error is utilized in lieu of robust standardized practice. Ultimately, as software workflows improve (e.g., through embedded process simulation), the need for the individual preparing a printing job to understand the physical relationship between her choices and component quality will be reduced. There is good reason to believe that software will develop to the point where build preparation can be performed by low-skilled workers with specific AM knowledge, or automated entirely. New and old software firms are simplifying the AM workflow by integrating various production steps (ranging from early stage parametric CAD modeling to post-machining of AM-produced components) within the same software ecosystem. In our experience teaching generative design principles and workflow to professionals, these skills can certainly be taught to a diverse audience with limited prior knowledge. The challenge will be to reconcile the *status quo*—which relies on overly skilled labor to perform routine tasks—with a more accessible future.

When these considerations are fully understood, the natural conclusion is that upskilling existing workers may be as critical as fostering new generations of qualified AM workers. Upskilling has several advantages: (1) Workers who acquire new skills already maintain a foundation of knowledge requisite to perform their roles in their specific industries, and thus firms can "trade" the costs of providing on-the-job training for new workers with the cost of upskilling experienced workers to perform new tasks; this should generally be less costly for the firm than hiring new workers. One survey associated new hires with 65 training hours and two months of onboarding before they reached peak levels of productivity. Uncaptured potential productivity amplifies the direct costs (quantified at approximately $4,000 per person) of training new workers. (2) Retained workers have firm- and industry-specific experience and knowledge that firms may wish to retain, since experienced employees are typically much more productive. Moreover, many firms struggle with the capture and propagation of "tribal knowledge" within their extant workforce; retaining critical workers with such knowledge is thus important to ensuring continued fluid operation of manufacturing processes. This is especially true when complex, cyber-physical production systems are considered. (3) Finally, experienced workers with newly acquired skills may be more capable of identifying applications for those skills if they are already familiar with the products and processes of the firm. Some have argued persuasively that investments in organizational learning can be directly correlated to improved innovation outcomes and, therefore, improved industrial performance. Such positive effects may not be guaranteed—for example, our case-study partner noted disappointment with the perceived lack of innovation seen despite workforce training investments—but the logic behind this argument remains intuitive and straightforward.

Our experience in authoring and managing the largest professional AM training initiative—MITxPRO's Additive Manufacturing for Innovative Design and Production, which has trained more than 4,000 professionals since its mid-2018 launch—may offer some insights on the upskilling of workers for AM environments. Specifically, entrance survey data collected on course launch compared two cohorts of students; the first cohort was composed of public enrollments (i.e., individual customers who signed up for the program independently), whereas the latter cohort was composed entirely of employees at a single major U.S. manufacturer. When asked about total work experience, both cohorts demonstrated a bimodal distribution in their responses. In both cases, the plurality of students had more than 15 years of work experience. The next highest category, in both cohorts, were employees with one to three years of experience. We may extrapolate from this that manufacturing firms recognize the significance of investing in workforce training initiatives to retain and upskill existing workers (the great majority of students in both cohorts were supported by a corporate learning initiative). However, it is somewhat surprising that the next largest category of students comprises relatively new workers. While this fact is challenging to interpret, it suggests that there may be a lag in efforts to integrate new manufacturing technologies into vocational and postsecondary training programs that is entrenching the aforementioned skills gap.

Arguably, despite the growth of AM-specific workforce training programs, additional investments are necessary to bolster the available workforce to help design, lead, and implement AM initiatives within manufacturing firms. Empirical data from firms such as the Boston Consulting Group and McKinsey and Company argue persuasively that education remains a significant impediment to wider adoption of AM processes. Given the broad applicability of AM processes across industries, and their increasing commercial uptake despite the challenges mentioned, it is our opinion that targeted investments in AM training programs will be key to producing a workforce capable of developing and leading the design and fabrication of novel products utilizing these methods. Though AM processes require some sophisticated skillsets where the engineering of components is concerned, it also requires myriad AM-specific supporting roles (e.g., machine operators or technicians) that are appropriate for vocational training initiatives. Given the relatively high cost of implementation—especially for more complex, metal-powder-based AM processes—it may be difficult for public educational institutions to afford the cost of integrating AM machinery with instructional curriculum. Grant programs may offset these costs, and new educational collaborations between industry and academic partners with appropriate facilities may be attractive options for expanding the scope of instructional content at a minimal marginal cost.

Implications of Additive Manufacturing

Despite the above-mentioned challenges, AM confers major advantages in the development and production of manufactured goods, in cases where it is deemed economically and operationally attractive. Though some of these advantages have been explored already—specifically, (1) AM does not require part-specific tooling, and (2) AM is inherently more flexible in which geometries it can reasonably produce—we will now discuss the implications of these advantages for various industrial and consumer purposes.

PRODUCT DESIGN AND PERFORMANCE

AM's unique properties enable the direct fabrication of parts with complex internal geometries, facilitating topology-driven performance optimization and consolidation of assemblies into single-part designs. For example, using metal AM, General Electric has developed enhanced jet engine and helicopter components, and Siemens Industrial Turbomachinery has established serial production of high-efficiency gas burners, among other products. Shape-optimized components (Figure 5) may perform mechanical functions with less weight than conventional components—a critical factor in reducing device operational cost and energy consumption, especially in transportation-related industries.

Product customization is a separate, but equally important, potential application of AM. Medical devices provide an ideal opportunity to leverage the geometric freedom and customization capability of AM. For example, AM enables mass-production of custom hearing aids with improved fit and audio quality; as a result, all major hearing-aid manufacturers switched exclusively to AM within 500 days of the release of Materialise's Rapid Shell Modeling software. Mass-market customization of other devices is likely to become economically viable as higher-throughput, lower-cost polymer systems continue to gain traction.

AM gives designers freedom to reimagine how end products are produced and configured, and integration of AM with conventionally made components allows companies to develop platform technologies that can be tailored to specific market segments. For example, several furniture designers have used AM to fabricate geometrically complex connectors, simplifying assembly and enabling a broader catalog of sizes and configurations. Burton has recently used polymer SLS to build high-performance snowboard bindings, which are an attractive choice because they are geometrically complex, high-performance products with frequent style turnover.

C*ustomer-specific products* can be tailored to individual users using AM. For instance, Atherton Bikes uses SLM to build topology-optimized, lightweight metal connectors for mountain bike frames; the connectors mate to carbon fiber tubes to create a unique frame for each customer. Nike, adidas, New Balance, Under Armour, and several start-up companies have discussed AM in the context of footwear; examples include cleats with complex geometries that enhance grip for athletic performance, customized soles for comfort, and on-demand manufacturing enabled by integrating AM with robotics.

AM can also enable *customer-specified products*, which engage the consumer directly in the design process. App-integrated marketplaces such as Toyze and Hero Forge sell models of popular multimedia or fantasy characters, enabling customers to design statuettes from a wide suite of models, positions, and accessories and have them printed as one-off products. Aoyoma Optical now uses polymer laser sintering to produce eyeglass frames, enabling customers to choose their preferred combinations of style, size, and color. The uses of AM for jewelry and other wearable and decorative artifacts are also growing rapidly, buoyed by design-driven businesses such as Nervous System, as well as service bureaus such as Shapeways and Materialise.

Ultimately, AM and other responsive, digitally driven manufacturing technologies will challenge traditional retail models for many products and will enable individuals to digitally access production infrastructure. On the one hand, increased involvement of consumers directly in the design and testing of purchases can offset the higher price point of AM products or drive differentiation of value. On the other hand, brokers of customized goods can promote a bespoke model, benefiting from the reduced holding costs of responsive inventories. AM can also be used to tailor product packaging; for example, rapid manufacturing of tooling for thermoformed packaging can enable logistics firms to create custom point-of-sale experiences for retailers, thereby better adapting to geographically or seasonally varying preferences.

OPERATIONAL PERFORMANCE

For many years, companies have used AM to create prototypes quickly, thus enabling rapid design evaluation and reducing product development times. Increasingly, small volumes of components made by AM are used in pilot product testing with customers. For example, according to PepsiCo, desktop 3D printers were used to create a cohort of two dozen plastic potato-chip prototypes for customer focus groups to judge by feel, aesthetic quality, and overall design. This feedback enabled faster and more accurate testing of prototype potato chips made using custom cutting tools and reduced the time to launch the new product. Wide availability of desktop polymer 3D printers has brought AM closer to many engineers and designers, and professional systems that use high-performance materials are finding increased application for mechanical hardware and fixtures throughout the product development cycle.

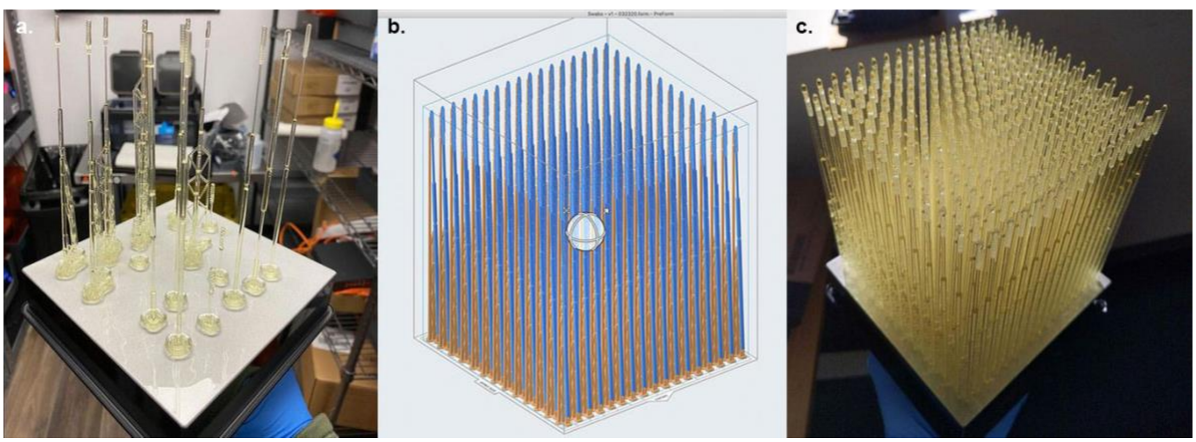
We investigated the use of AM in product development initiatives as part of our research. Through more than a dozen conversations with workers at the aforementioned large industrial user of AM, we found that the unique characteristics of AM impel firms to make corresponding changes in the arrangement and execution of their development activities. On the one hand, the trial-and-error method intrinsic to many deployments of AM requires greater connectivity between distributed functional groups. Product designers, for example, must work hand in hand with test engineers and AM technicians to arrive at the right combination of geometry and production strategy. These roles may otherwise be segmented when conventionally manufactured products are considered insofar as the test regime for those products is unlikely to reveal the need for significant alterations in the component's design. This reinforces the dynamic that has made highly qualified labor a significant subset of the AM workforce, as design engineers are tasked with greater interdependency and cooperation with other functional groups. Specifically, participants identified a shift from simulation-based prequalification of candidate design components to physical prototyping and destructive testing, a change that reflects the relative immaturity of AM simulation software and certification data. To a certain extent, experimentation during product development may be greater with AM technologies than conventional ones due to these dynamics at present; case study participants caution that organizations seeking to adopt AM must be cognizant of, and willing to bear, the cost and risk associated with technology development. Once successful, however, "lighthouse projects" can develop important internal competencies and demonstrate convincing results for further exploration of AM applications within a firms' product catalog.

At the same time, AM is creating new efficiencies in concurrent engineering practices. Typically, product development activities are performed in sequence: information that is codified via an early development activity (e.g., component's design is frozen) is utilized for subsequent activities (e.g., tooling design). Concurrent engineering methods seek to minimize the temporal distance between adjacent development activities and instead perform them, to the extent possible, in parallel. This approach minimizes the labor costs associated with project-dedicated personnel and enables faster times to market, which can be strongly advantageous for first-mover or other market effects. Importantly, research has demonstrated that the degree of parallelization is itself a parameter that must be tuned, as resources are committed based on working assumptions rather than formal decisions. Put simply, the greater the level of uncertainty in upstream processes, the more likely it is that downstream processes will need to be reworked to account for previous changes. Rework is considered inherently unproductive, since the initial resource investment to perform a stage has to be duplicated to account for revised information.

In comparison, the trade-off between information certainty and parallelization of development activities is less significant in AM than in conventionally tooled manufacturing. Critically, because AM components do not require part-specific tooling, decisions about the final component design can be made later in the design process; the associated lead time for preparing tooling is no longer a determining factor. Prototypes can be prepared more quickly and in greater quantities because the final product will be manufactured according to the same process as the prototype, which means prototype tooling is not required. Moreover, the act of physically prototyping components, rather than digitally prototyping candidate geometries through computational simulation, enables greater exploration of the available design space during early stage design ideation.

Design and product development flexibility are paramount to the realization of agile manufacturing systems. Rapidly changing consumer preferences and supply-chain disruptions due to environmental or political crises pose significant risks for reliably determining both supply and demand. Configurable production assets, including AM systems, may enable firms to respond quickly in periods of uncertainty to pivot their production activities as needed. During the 2020 COVID-19 public health emergency, AM-enabled firms were quick to leverage existing production infrastructure and prequalified medical-grade materials for the production of nasopharyngeal swabs (Figure 11). The project, initiated by faculty at Harvard, MIT, and in collaboration with companies Desktop Metal, Formlabs, Carbon, and others, resulted in the production of millions of swabs per week only a few weeks after initiation.

Figure 11. 3D Printing of Nasopharyngeal Swabs



(a) Prototype swab designs on a build platform. (b) Software preview of a swab production run. (c) Array of as-printed nasopharyngeal swabs. Source: Formlabs

Even when AM is not used as the principal production method, however, it can improve operational processes and expedite production tasks. AM is widely used to fabricate polymer tooling for prototype sheet-forming and injection molding, as well as metal tooling with complex cooling pathways that reduce cycle time (i.e., the time for one molding cycle) and improve dimensional accuracy. The latter can justify the significantly greater cost of AM tooling, which often requires conventional machining and polishing for end use and relies on highly refined hands-on expertise. AM can also be used to enhance human productivity, such as by producing worker-specific splints to reduce joint stress and fatigue, and, eventually, custom lightweight exoskeletons to augment strength.

Emerging high-rate AM equipment and its integration in automated systems that produce finished parts will enable broader access to AM for volume production while driving continuous improvement of the breakeven point (Figure 7c) when compared with conventional methods. For example, integrated automation for selective laser melting is under development by several manufacturers, and pilot production lines for polymer AM have been demonstrated. Motivated by this promise, major logistics companies, retailers, and manufacturers such as UPS, Amazon, and Mercedes-Benz have publicized initiatives focused on AM-based virtual warehousing, especially for service parts. At present, few production parts are directly suitable for this purpose given the limited material, dimensional, and surface-finish capabilities of AM. However, when these requirements (including post-processing) on-demand production at the incremental cost of AM can be envisioned.

ENVIRONMENTAL IMPACT

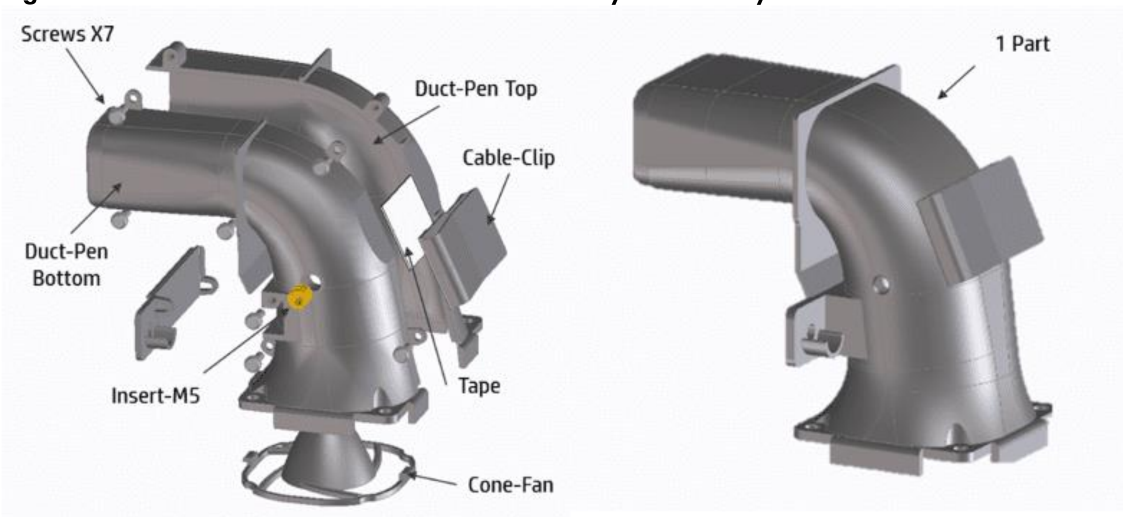
AM processes are generally less energy-efficient per volume of formed material than other bulk-forming processes. However, the technology's unique capabilities may enable beneficial environmental effects at the application level. AM-enabled design of shape-optimized structural components with reduced mass can result in downstream energy savings in use. Airbus, for example, estimated that if it were to replace each of four partitions inside its list of back-ordered A320 passenger aircraft with a lightweight additively manufacturing alternative, approximately 465,000 metric tons of carbon dioxide emissions would be eliminated over the course of a year.

Figure 12. AM of a Hydraulic Manifold

LEFT: A hydraulic manifold made by machining of a block of metal. RIGHT: Rendering of a performance-optimized hydraulic manifold, printed in a single-piece using selective laser melting. Source: Renishaw

Moreover, AM processes may introduce efficiencies into the assembly of complex components. Given the constraints on conventional manufacturing processes, highly complex components are often manufactured into discrete subassemblies composed of many parts. These parts are then joined, fastened, or bonded together to form the finished component. AM's design freedom allows firms to minimize assembly complexity (e.g., consider the manufacturing complexity required to produce the hydraulic manifold shown in Figure 12, which was printed as a single piece). Manufacturers such as Hewlett-Packard and General Electric, which are also producers of AM systems, are pioneers in using AM for assembly consolidation (Figure 13). While assembly consolidation may save manufacturers lead time and cost, its environmental implications are equally important; as the number of process steps or the types of forming processes utilized decreases, the per-part energy cost of forming the material is likely to decrease as well. Moreover, depending on how the firm has configured its supply chain, AM systems also offer the potential to consolidate production of diverse geometries in a single production site. The fewer geographic nodes in the supply chain, the less energy is used in the transportation of unfinished goods to and from manufacturing locations.

Figure 13. Part Consolidation of Air Duct Assembly Enabled by AM



LEFT: Multi-part assembly designed for injection molding and mechanical fastening. RIGHT: Single-piece component produced using HP's multi-jet fusion technology. Source: Fastradius/HP

Finally, the use of AM for repair applications may extend the useful service life of many components, reducing the overall consumption of material (and energy to form it) for both manufacturers and home users of AM systems. From the industrial perspective, metal AM technologies have been used for spot repair of components, from RPM Innovation's laser cladding of worn precision shafts, to Siemens' use of laser powder-bed fusion for the repair of gas turbine components. These applications extend the duration of the original component's lifetime with marginal resource expenditure when compared to a complete replacement using a newly manufactured spare part. The French firm Happy3D, a spinout of home goods retailer Boulanger, has created an entire business out of consumer self-repair of appliances. AM is therefore an essential enabler of the "Right to Repair" movement, which argues in favor of legislation enabling home users to perform self-modifications or maintenance on their owned objects without voiding specific liability or warranty protections. iFixIt, a website dedicated to the repair of common consumer products, for example, ran a challenge in 2018 dedicated to AM use cases in home repair.

Though issues remain with respect to recycling or reprocessing of AM-produced objects, the technology's intrinsic flexibility allows us to envision the realization of circular economies for various goods. In this vision, parts are produced and maintained additively, with replacements produced on demand without the economic constraints of fixed production tooling. After their useful life has ended, parts are reprocessed into feedstock for future components which, again due to AM's flexibility, may be of a completely different nature than the component the material was used for initially. Enabling this future will require further scientific development, particularly with respect to the treatment of material, but the commensurate infrastructure (including standardization, high-fidelity data sharing, and so forth) is maturing rapidly through the contributions of the industrial community.

HOME FABRICATION

It has been suggested that AM systems will become as simple to operate, as popular to own, and as routine to use as the microwave oven or home (2D) printer. While this broad vision appears unrealistic, there are ways in which AM can benefit individuals. Consumers with access to specific software and hardware tools are increasingly able to utilize AM systems for a variety of personal purposes, such as to produce bespoke ornaments and other functional home goods (e.g., vases, lithophanes, or shelf spacers), replacement parts for home appliances (e.g., knobs, casters, and so forth), and for various hobby purposes (e.g., to produce jigs for woodworking tasks or holders for fishing equipment). Networked communities of these users (e.g., on the popular social media platform Reddit's "r/functionalprint" community) share best practices and sample projects to serve as guidance or inspiration. The ongoing maintenance of user-friendly and free-to-use software tools (e.g., Ultimaker's Cura or Autodesk's MeshMixer), as well as the decreasing cost of reliable, high-quality consumer desktop-style AM hardware systems (e.g., the popular Creality Ender 3, which retails at just above $200 as of this writing), are reducing barriers to entry by consumers and hobbyists. There is also evidence to suggest that the hobbyist community—and personal, as well as professional ownership of consumer-grade 3D printers—is growing. In 2019, Wohlers Associates estimated the total sales volume of desktop systems exceeded 700,000 units globally, a 19 percent increase in unit sales from the prior year, marking the 12th consecutive year of consistent growth since the firm began tracking sales of this style of printer.

The potential ubiquity of AM for consumer audiences poses significant questions, not the least of which is related to the maintenance of various household goods and appliances. Manufacturers of consumer products are increasingly interested in limiting the repair of their products to specific technicians. As devices become more sophisticated, including with wireless connectivity and computerized in-device monitoring systems, the ability of original equipment manufacturers (OEMs) to restrict the repair and maintenance of devices has increased via the use of electronic security mechanisms. Today, the refurbishment of damaged goods may require not just a mechanical repair but a repair and update to the corresponding software necessary for the devices' function. Moreover, in the case of the automotive industry especially, access to device-monitoring software may be necessary for identifying the causes of device malfunction. In some cases, limiting repair may be a technical necessity given the inseparability of proprietary software, electronic components, and mechanical parts within a given device. However, as Perzanowski (2020) argues, firms have deployed various strategies unrelated to technical feasibility to curtail product repair. These strategies span legal injunctions, pricing strategies, product design, warranty policies, and so forth. In some cases, these practices are transparent and integrated into a firms' core growth strategy. Changes in OEM policy have also been matched, in some cases, by adjacent industries: the world's leading internet advertiser, Google, for example, updated its advertising policy to restrict its services from "third-party technical support," which includes "hardware support and repairs."

As a result, OEMs for various goods, including most prominently Apple, have drawn public scrutiny over prospective restrictions on what entities are entitled and capable to perform device repairs. While there are compelling reasons for these changes—including, for example, liability and warranty protection as well as the collection of important device performance feedback for future product iterations—third-party repair technicians and cost-sensitive consumers have balked at the prospect of reduced consumer options and the perception of higher costs or intentionally poor service due to "planned obsolescence." The right-to-repair movement, in response, has launched legislative initiatives in several states seeking to prohibit what it considers to be unreasonable restrictions on aftermarket service of various consumer goods and devices.

The push-and-pull between OEMs and interested third parties largely concerns the use of software as a regulator in repair activities, but AM processes are centrally important to this discussion. Whereas a conventional home repair may require, for example, the purchase of an aftermarket third-party component, desktop AM systems may enable consumers to produce such components themselves. For simple mechanical components, hobbyist users may even have access to low-cost, handheld scanning devices (such as 3D Systems' Sense 2 Scanner, which retailed for $399) that can extract digital geometry from a physical good for quick replication using the AM system. The increasing popularity and accessibility of the devices needed for such a workflow poses potential challenges to the continued financial growth of third-party repair firms (which may, instead, find themselves adopting the same workflows for their projects) as well as to the sustainability of aftermarket services from the OEM itself. Ownership of digital information is a potential challenge as well: if a consumer creates a coarse replica of a given component geometry using software and hardware owned by the consumer, is that consumer *also* the owner of the digital facsimile that was extracted, or does that remain with the OEM? And, does the same intellectual property scheme apply when a geometry is *re-created* by the direct labor of the consumer (i.e., an approximation instead of replica) rather than extracted in semi-automated fashion from the component using a 3D scanner? If such rights are retained by the OEM, how can they be meaningfully enforced? What notifications must be given to the consumer, for whom it may be impossible to accurately parse which components are intellectual property, and which are common, off-the-shelf parts? Conversely, should a consumer use AM to augment a device (e.g., through printing custom connectors, spacers, or so forth), to what extent is that customer able to pursue property protections for her invention?

If potential repair files are prepared and uploaded by well-intentioned users under Creative Commons licenses (as is often the case with Thingiverse, a popular website for free-to-use design files used by the hobbyist printing community), liability in the case of device failure may not be immediately attributable or, worse, may rest in the hands of the well-intentioned uploader of the design. It may further be the case that such files are not designed with noble intent. The use of deceptive digital practices has risen, upping the risks associated with downloading, producing, and using files of unknown origin or quality.

Finally, the home use of AM poses sustainability issues. Many desktop systems operate via extrusion of thermoplastic materials, much of which is needed only during the printing phase, after which it is discarded. Additionally, it is often the case that prints do not resolve successfully upon the first attempt, which means there is waste associated with the iteration necessary to fine-tune a particular print before the component can be produced at an acceptable level of quality and accuracy. Should printers become a staple in every home, the consumption and waste of non-degradable polymers may increase.

How realistic are these risks? It is not our opinion, as of this writing, that these challenges will manifest themselves on a grand scale in the immediate future. Though the global sale of desktop AM machines is significant, it pales in comparison to the approximately 7 million microwaves sold domestically within the United States alone each year. Moreover, there are a variety of enterprises that purchase desktop AM equipment for commercial use-cases, and it is highly unlikely that all 700,000 units sold in 2019 were purchased by individuals rather than firms (we would argue that a significant fraction of these lower-cost systems are put to industrial use). With respect to the prospective sustainability challenges raised by home fabrication, it is not evident that these challenges will eclipse the waste generated by the purchase of substitute goods in cases where home fabrication is not available. It is further possible that, should self-repair using AM systems become increasingly prominent, there could be a net-positive environmental effect through the elimination of transportation-related carbon emissions, reduced new product manufacturing, and the increased lifetime of home appliances.

However, the dual trends of increasingly restrictive policies toward the repair of purchased goods and the increased ease of preparing mechanical replacement components will persist as AM systems become more widespread. Realistically, desktop consumer-grade AM systems often produce components with quality compromises that would be unacceptable for OEMs. While this may limit the applicable range of AM in home fabrication activities, it may also lead to an increased risk of injury or device malfunction for consumers. For this reason, it is important that legislation keep pace with the rate of technological change in order to narrowly tailor restrictions based on the state of the art. Without such synergy, it is likely that policy options will remain either too risk-averse or too *laissez-faire* with respect to the safety and liability associated with home repair activities.

PIRACY, INTELLECTUAL PROPERTY, AND ESPIONAGE.

We have addressed the significance of AM with respect to the protection of intellectual property in consumer use cases. Yet more broadly, the rapid realization of counterfeit goods may be possible through sophisticated workflows that combine digital geometry reconstructive tools (i.e., scanning) and AM processes.

Counterfeits are a persistent problem today. Representatives from Toyota Australia, for example, stated in 2018 that more than a third of "genuine" Toyota products available online were counterfeit. Counterfeit parts pose several risks. First, their production is a form of rent-seeking behavior, where counterfeiters capture economic rents due to the OEM by leveraging the brand identity and integrity of the product being counterfeited. Second, they damage consumer protections, especially when warranty protections are contractually affixed to the use of certified components in a given device or appliance. Manufacturers of counterfeit goods may not apply similar quality management procedures as the OEM, and their products may not be regulated in the same way. In 2012, for example, the National Highway and Traffic Safety Administration warned about the risks of counterfeit airbags; in 2017, counterfeit airbags were linked to the tragic death of a motorist after a crash. It is no surprise that major manufacturers—including those who produce devices with stringent safety standards such as automotive and aerospace manufacturers—dedicate significant resources to supplier validation and training supply-chain personnel to mitigate the risk of introducing counterfeit parts into their products. The risks associated with device failure include not only danger to the user, but significant liability risks to the manufacturer or assembler of the finished product.

Though counterfeit devices are not a novel challenge, AM arguably reduces the barrier to entry for a prospective device counterfeiter. As we have already discussed, AM processes are capable of handling a wide range of materials and component sizes. Optical and dimensional differences in counterfeit and OEM-produced components help enable regulators and manufacturing entities to identity and eliminate counterfeit goods from finished components or supply chains. If the capture and translation of geometry into digital form is sufficiently accurate, AM systems may one day become enablers of counterfeit goods; this is especially concerning insofar as AM may simplify the replication of a component by eliminating the need for a firm to design the associated tooling to produce the counterfeit good. Additionally, certain AM processes are increasingly capable of producing photorealistic, fully colored, and materially diverse components. While advantageous for legitimate commercial purposes (such as prototyping or focus-group engagement), these strengths may open up commercial risk through the simplification of counterfeit workflows in cases in which multiple materials or multiple colors are utilized in the finished part. If manufacturers are to realize the potential benefits of AM for the production of spare parts, they must apply significant attention to ensuring that the products they manufacture are of commensurate quality to their conventionally manufactured goods, especially when third-party suppliers are used. In general, we believe that counterfeiting using AM is unlikely to be widespread. The same cost constraints that throttle its adoption for legitimate commercial activity are also likely to throttle its utilization for illegitimate activities. In cases where deeply nefarious purposes exist for the counterfeiting (such as intentional sabotage during war) or the object is of significant value (such as a medical devices or prestigious artwork), purchasers and supply-chain professionals will have to be diligent about ensuring the quality and veracity of purchased components. Several research initiatives have demonstrated the use of embedded features and other identifiers to help authenticate AM components; still, the commercial feasibility and true security of these early efforts has yet to be determined. Other methods (such as the utilization of information-encoded polymer microparticles or spectrally unique nanomaterial coatings) for applying secure physical “tags” after AM is completed may be the most attractive solution to this problem.

Outside of issues related to physical production, AM processes may also invite risk in the preparation and dissemination of digital information. In 2014, for example, a former United Technologies Corporation (UTC) engineer, who worked on additive manufacturing projects at UTC subsidiary Pratt & Whitney, was arrested for violating the International Traffic in Arms Regulation. The individual possessed a series of physical documents containing trade secrets related to the technology employed in the production of commercial and defense-oriented aircraft. Separately, Cody Wilson’s “Liberator” firearm made headlines in 2013 after the files for the weapon—fully 3D-printable in plastic—were downloaded more than 100,000 times in just two days. Though the concern over printed firearms was justified, in practice the process of their production was unlikely to yield significant consequences. AM is rarely a “first-time-right” process; rather, it requires specific technical knowledge at the intersection of component design, manufacturing strategy (i.e., how the parts will be arranged within the build volume), and execution (i.e., what post-processing must be performed and in which manner). Moreover, within the United States, it is unclear if criminal actors would be able to acquire sufficient AM expertise to reasonably produce these firearms at comparable quality to commercially manufactured firearms, which can be purchased widely. Moreover, there were significant questions about durability and user risk; in some test scenarios, the 3D-printed firearm was shown to explode as the hammer struck the bullet, posing significant danger to the operator. However, these anecdotes nonetheless raise considerable concerns about the propagation of the digital information used to describe and produce AM components.

In particular, the preparation, distribution, and utilization of digital information poses two specific risks. (1) Rogue actors—either commercial entities, or actors working on behalf of state bodies—may capture and disseminate trade secrets for the purpose of damaging the commercial interests of their competitors or firms central to national security (e.g., major aerospace and defense firms). Reverse engineering of security-critical devices, for example, was undertaken as recently as 2011 by the Iranian Revolutionary Guard Corps after a Lockheed Martin unmanned aerial vehicle was captured. While these risks are not unique to AM—in any instance where digital information is transferred, the risk of it being utilized for subversive purpose remains—AM may facilitate the translation of that data into practice. Insofar as AM processes are becoming increasingly capable, do not require part-specific tooling, and can simplify complex assemblies into print-in-place single components, AM may also simplify the supply chain requisite to reproduce stolen designs. (2) Intentional sabotage may be performed by weaponizing digital information to intentionally induce machine failure, similar to the intention (albeit not of the same magnitude) of the Stuxnet worm used to catastrophically damage Iranian nuclear facilities. Additionally, there is concern that intentional sabotage and counterfeiting activities may be intertwined; a hostile body might produce counterfeit goods intentionally designed to fail or alter the base file of an AM-produced component to invite component failure. For example, the intentional addition of voids to AM components may significantly reduce component strength yet remain invisible during an optical inspection. It is difficult to quantify the likelihood of these risks, given that the same challenges that stymie the use of AM for industrial uses (such as a limited supply of skilled workers) will hamper the ability of rogue actors to execute these attacks.

Though both risks are of some concern, myriad physical and digital security mechanisms are deployed regularly that would protect against these efforts. Nonetheless, we feel that government and industry must be intentional about mitigating these risks; industry must use robust security architecture that makes intentionally deleterious activities significantly challenging, if not impossible, to execute. With respect to counterfeit goods, incorporating physically realized serial numbers and other part-specific identifiers has been suggested. With respect to digital file transfer, the incorporation of part-specific identifier keys matched uniquely with a corresponding production machine have been suggested. Further, the maturation of file formats for AM processes will enable greater file security through standardized encryption protocols. While industry must remain abreast of risks and proactively seek to combat them, it is equally important that security developments are harmoniously integrated into defense-critical sectors where commercial experience may augment government agencies' ability to secure the production of goods needed for warfighting or other defense purposes.

SEGMENTATION OF DESIGN AND PRODUCTION ACTIVITIES

The complex relationship between a component's design and its manufacturing workflow is reified repeatedly throughout conventional manufacturing processes; changes to a component's geometry must be propagated to a series of planning activities, such as tooling design, assembly floor layout, and so forth. A typical product development process will involve a series of design iterations after which a design must be frozen and converted into a manufacturing plan that includes part-specific tooling, assembly procedures, finishing operations, and other production tasks. These plans are identified and also frozen before the component can be converted from drawing to physical form for end use. As we have discussed previously, AM fundamentally disrupts the linearity of design activities by enabling rapid design evolutions to occur without a commensurate waterfall of changes being needed to produce the component in defined production quantities. This is not to say that iteration for AM has negligible cost or other implications but to emphasize that the intensity of a redesign effort is limited when comparing AM components to their tooled counterparts. Importantly, these implications may be felt beyond a specific organizational workflow and extend into the constitution and value propositions of entire enterprises.

The idea of a firm specializing in a specific production activity (e.g., casting) is not one only made possible through AM. For example, ThomasNet, the leading database of United States–based contract manufacturers, has more than 2,300 firms registered that offer casting services of various kinds. Importantly, however, when contract manufacturers are utilized, it is sometimes the case that their performance is limited to the physical act of forming the components. While there may be iteration between the OEM and the contract supplier on the exact manufacturing approach, the ultimate responsibility for designing production tools rests in the hands of the OEM insofar as the design of such tools is critical for cost control and quality assurance. Moreover, such tools, including the intellectual property embodied in their design, are owned by the OEM even if they are used by a third-party contractor. Though some OEMs may significantly rely on the expertise of the contractor to design tooling, for complex engineered goods or large enterprises this is not often the case. It is therefore not possible to say that there is a true demarcation between design and production activities, since the production workflow is intrinsically connected to a components' design in *status quo* manufacturing activities.

Yet, AM offers some opportunity to further demarcate these two halves of a manufacturing operation. The innate reconfigurability of AM machinery—requiring only changes executed via software to produce different components—suggests that contract firms may be able to offer a much wider variety of components in the future. AM service bureaus may become flexible production facilities serving a broad category of industries and consumer types. Already, there are many new firms specializing in the production of AM components. Direct producers such as Protolabs, Shapeways, and Fathom own and operate their own AM facilities and have seen rapid growth in their AM services over the years. Given that AM, at present, is more often economically advantageous in limited production runs, it can make sense for manufacturers to pursue production using third-party services, especially when the costs of machinery installation (which may exceed the cost of the machine itself) are considered.

Indirect producers, or those who maintain database networks of various contract firms, are also becoming common. Xometry, which boasts a network of more than 6,000 manufacturers and specializes in AM processes, has raised $193 million over the past seven years. Xometry is able to operate efficiently due to its engineered approach to the reverse auction. Customers use Xometry's website to submit digital files, which are read and analyzed in near real time. Xometry's software then recommends specific combinations of manufacturing processes, lead times, and pricing among which the customer may choose. Importantly, Xometry not only includes AM producers but also many conventional processes as options. Xometry's business model is enabled uniquely through the rapid dissemination of component data that is cross-mapped against a distributed global network of production machinery.

AM-supported production networks are enabled by the fact that, for certain components and AM processes, it may be possible to pack different components for various customers into the same production run. Hitch3D, a Singaporean start-up established in 2017, offers a unique type of contract service: the firm itself neither owns nor operates a single AM system. Customers submit CAD files for printing in the same way they would if using a service such as Xometry. These drawings are then disseminated to Hitch3D's network of AM service providers and, when excess capacity inside a production run can be allocated to the component, the requester "hitches a ride" in a job run to save cost and increase production speed. Though this model is only suitable for very small runs of components, it indicates the possibilities of a flexible production infrastructure, tunable in real time to a client's requirements.

In sum, these trends beg the question: how will production activity be distributed in the future? Should AM's value propositions become fully realized and usher in an era of greater product flexibility and end-user customization, the idea of utilizing quick-turn, flexible, and nondedicated contract production services may become increasingly appealing. Distributed production activities may engender new opportunities for value capture through accelerated time to market and regional product differentiation. If this future is to be realized, it may require a mature infrastructure of production-oriented facilities with corresponding data architectures and digital assets that make production conversion from component to component seamless and error-free. Moreover, the separation of design and production activities may enable firms to pivot the locus of their workforce; rather than spread energies across the entire product development process, firms may decide to specialize in the design of products to be handed off to third parties for production and finishing. AM's intrinsic flexibility could enable this future insofar as manufacturers need be less concerned (though not completely agnostic) about the physical execution of the production process, especially in the case of products with less-rigorous functional requirements.

There are already a few examples. Hero Forge is a small business that hosts a web-based configurator for customized desktop miniatures used in tabletop games and as ornaments. Customers have a wide variety of custom options, which are parametrically modeled via an automated tool to generate the desired miniature in real time. After a customer has chosen a design and placed an order, Hero Forge automatically delivers the file to a third party, Shapeways, which then prints and fulfills the order. Hero Forge can thus be considered as a manufacturer that neither owns nor operates a physical production facility. Another firm might not even own physical computing facilities, renting them on a marginal basis from a cloud-service such as Amazon Web Services. 3DBean, a Boston-based company, practices "3D photography" by capturing 360-degree, three-dimensional renderings of a person or object. The rendering is again sent to Shapeways, which converts it into a physical replica to be sold to the customer. In both these cases, the firm that "produces" the product is wholly uninvolved in the physical production activity beyond the transfer of digital information.

At present, it is difficult to say that distributed, on-demand production enabled by AM will be realized for large firms, or more complex products, in the near term. As we have described, serious technical challenges must be overcome to ensure the repeatability of AM processes across locations, and the time-intensity of engineering even a single AM application where the component must be qualified for structural uses is a laborious and costly undertaking. As long as this remains the case, the design *and* production of sophisticated AM applications will remain largely within the domain of the OEM. This is especially true considering that application development for AM can be considered a lever of competitive advantage; the cultivation of knowledge internally enables firms to produce products of greater performance than their competitors. Given the talent gap noted among qualified AM professionals, firms have a competitive interest in securing qualified workers to ensure the success of their AM ventures, rather than relying wholly on the expertise of external parties.

To truly realize the rapid and distributed production potential of AM, it must be integrated with overall production activities—including secondary manufacturing processes, assembly, quality control, and so forth. Data warehouses that combine the networked capabilities of different facilities—and interface with the machinery within those facilities—will enable on-demand and site-indifferent production. In such a future, orders for components that can be made using digital production methods could be placed by the OEM automatically in response to variable local demand or inventory. Orders would be triaged to locations meeting both technical and economic specifications, and the digital information transferred to the production partner would not only include the component geometry but any specific manufacturing instructions necessary to realize the finished product. The myriad challenges and implications we have explored thus far will continue to prohibit the realization of this vision for years to come. However, it is inevitable, given the trajectory of the AM industry and the global emphasis on digital transformation, that such ideas will move forward steadily.

DISTRIBUTED AND REMOTE PRODUCTION

Finally, we consider what a complete maturation of AM processes may enable for large, multinational manufacturing firms. Should the aforementioned technological obstacles be overcome, and the quality and throughput of AM systems mature to the point where parts can be made identically across production facilities and machine architectures, AM's immutable and unique value propositions compel us to speculate on what this might mean for future supply chains and product designs.

Most obviously, AM may enable a future where the fulfillment of spare parts is done wholly by digital manufacturing (when possible given component performance and quality considerations). Though the philosophy of just-in-time production has recently come under scrutiny due to the disruption of global supply chains during the COVID-19 pandemic, inarguably the optimization of inventory enables greater efficiencies and reduces the cost burden on manufacturing firms associated with warehousing. AM may also mitigate supply-chain disruptions since its production capacity is tunable to demand rather than affixed to production volume, and AM can be locally placed. Should manufacturers be equally flexible in their preferred production partners and geographies, it may be possible to sidestep the schedule delays induced by import-export regulations or the closure of specific ports of entry through the temporary activation of production sites within the country where the component will be used. In one case study that evaluated the use of AM for spare parts production, it was found that the greatest advantage associated with AM was in the significant reduction in lead time associated with component fulfillment. Importantly, such flexibility requires that production facilities are either capable of periodically deprioritizing scheduled work to accommodate urgent orders or, conversely, that there is intrinsic overcapacity within the production system such that it can accept volatility and periodic spikes in machine utilization.

Increasing sophistication in manufacturing execution system software, and its interconnectivity with specific suppliers based on rules-driven approaches that connect user input to optimal production facilities, would minimize the operational burden to firms and unlock the potential of AM machinery. Though it is less likely that mass-market products will be fulfilled on demand due to cost considerations, for products where customization is considered a significant driver of consumer interest, this idea is greatly appealing.

There are many ways in which reducing downtime through rapid spare parts fulfillment is economically advantageous. In one study of the oil and gas sector, operational downtime at an offshore oil rig of just 3.65 days per year (1 percent of theoretically maximal uptime) was associated with expenses exceeding $5 million. For firms in similarly time-sensitive situations—such as energy generation or transnational shipping, or any significant revenue-generating operation—the costs associated with downtime are significant and can create unanticipated financial burdens. The U.S. Navy, for instance, has actively explored the use of printers operated entirely upon warfighting ships for the purposes of rapid maintenance. For facilities in remote locations, such as offshore oil rigs or wind turbines, co-locating AM systems in geographically proximate countries may be strongly advantageous for minimizing the associated costs of downtime.

Though this scenario is attractive, it requires that multiple challenges be addressed—many of which we have mentioned. It is likely infeasible for the OEM itself to maintain and operate each flexible production facility, given that the respective demands on these facilities would be highly variable depending upon the maintenance requirements of the machinery the facility services. The economic costs associated with retaining labor for variable work demands would also compete against the economic return generated by reduced lead times. Thus, we can safely conclude that enabling a distributed production network would require industry to resolve the two-pronged challenges of digital security and AM-based production variation, issues discussed earlier. Although innovation will certainly occur asynchronously through commercial efforts, we believe it is necessary for public agencies, professional societies, and academic institutions to continue their work in maturing AM systems and technology and in disseminating their findings through commercialization activities. The nascency of AM for serial production applications, in concert with its compelling value propositions, encourages firms to develop and retain AM-specific knowledge as a tool for competitive benefit. While this is likely to advantage large firms with access to working capital that can be dedicated to developmental initiatives, small- and medium-sized enterprises may find themselves priced out of this knowledge, and therefore less able to compete with larger enterprises.

Finally, we must consider not only the competitive interests of domestic manufacturers, but also national strategic interests—notably in terms of resilience to catastrophic crises. As a consortium of AM manufacturers and medical device firms demonstrated in early 2020, rapid product innovation with bridge fulfillment through AM can be successfully performed to fulfill products needed for emergency management. Many millions of 3D-printed nasopharyngeal swabs, mentioned above, have been used for the testing and diagnosis of COVID-19 patients. Other events that may disrupt the transportation of physical goods (such as trade embargoes, explicit conflict, or environmental disaster) will have similarly deleterious effects on quality of life for affected persons. AM systems that can be rapidly deployed to help build temporary housing, for example, or to repair failing infrastructure, could be critically important to mitigating the damage caused by such adverse events. From a security perspective, AM production facilities ought to be seriously considered as a latent strategic installation that can be activated on demand to bridge gaps in the production or fulfillment of critically important goods.

Industry Scenarios

Taken in total, the introduction of AM systems at both the consumer and industrial levels, and the respective maturation of both markets, raises the prospect of new product introductions and operational efficiencies previously unattainable. The bulk of this writing has been dedicated to describing these frontiers through several different perspectives. In this remaining section, we concretize these implications by exploring scenarios for three major U.S. industries: aerospace and defense, medical devices, and automotive vehicles.

AEROSPACE AND DEFENSE

Aerospace and defense firms have been among the earliest adopters of AM technologies. Given the extreme complexity and cost associated with the introduction of new aircraft to the market, as well as the relatively low production volumes for finished units, the industry is generally not as cost-sensitive as those concerned with high-volume, mass-market products. Instead, aerospace and defense firms are concerned principally with the quality and performance of their products given the potentially catastrophic risks associated with failure. From an operational perspective, the cost of production activities may also be generally less important than the time those activities require, since comparatively few units are fulfilled within a given time increment. It is intuitive, then, that aerospace firms have long used AM to help expedite production activities (through prototyping, tool production, and so forth) and have considerable interest in developing AM applications (such as shape optimization for reducing the weight of components) that can be qualified and deployed inside products. Relative cost-insensitivity coupled with high performance premiums justify the use of AM already, and aerospace manufacturers are at the forefront of advancing research and professional practice into the standardization and qualification of AM production processes and components.

At present, AM in this industry is used principally to assist production activities. In the near term, we are likely to observe many more printed components inside aircraft. Initially, these may remain primarily of use for nonstructural components (such as electronics housings, seat components, and so forth); however, structural applications have been qualified for use already and more are likely forthcoming. New approaches to materials—both the discovery and utilization of novel composites, as well as the adoption of engineered microstructural properties for metals—will further enable AM to find valuable applications.

The potential benefits of such optimization are difficult to quantify, but it is hard to overstate the potential environmental implications of weight-optimized aircraft. In 2018, commercial aviation was responsible for 2.4 percent of global CO_2 emissions or 918 million metric tons—a value which, though small relative to some other sources of global carbon emissions, represented a 32 percent increase over the preceding five years. In practice, aircraft that are lighter will consume less fuel and thus reduce the industry's overall carbon footprint; since more than 39 million passenger flights were taken in 2018, there is considerable opportunity for environmental and economic benefit.

Over the longer term, aerospace manufacturers may utilize AM processes to add efficiencies to their supply chains. As component counts are reduced and assembly tasks eliminated, supply chains may condense, placing greater emphasis on fewer more capable production sites. Moreover, spare-part fulfillment may be managed via a broad network of trusted suppliers distributed globally. Should airplanes be grounded, spare parts could be rapidly produced and maintenance performed by accessing geographically proximate AM production facilities for component fulfillment. Though spare-parts fulfillment is already performed rapidly in the case of grounded aircraft, it may be the case that maintenance, repair, and operations fulfillment centers will reduce inventories and instead rely on AM to meet needs on demand. As the throughput and digital connectivity of AM processes increases, it may be come feasible, for certain components, to produce them reactively and only when maintenance is required. However, given the centrality of the aerospace industry to national defense, addressing the risks associated with the control of intellectual property and the securitization of machine systems will be critical to facilitating distributed production activities. Thus, we expect that while aerospace will continue to push the frontiers of AM, it will be bounded in its future pending the maturation of a resilient and secure digital infrastructure.

MEDICAL DEVICES

The medical device industry, like aerospace and defense, is a highly regulated industry with significant premiums associated with marginal increases in device performance. In this sector, AM invites significant opportunities for device improvement through the combined factors of high geometric complexity and cost-indifferent product customization. For certain categories of medical procedures, including arthroplasty and reconstructive procedures, AM has already been integrated into clinical practice. Hundreds of thousands of patients worldwide have received hip implants produced via metal AM processes, which feature a highly porous surface geometry more conducive to osseointegration (the fusion of bone and implant)—a requisite for long-term implant success. The geometric complexity of orthopedic implants, and their high value, suggests that a significant fraction (if not all) implant manufacturing in the future will involve AM.

Moreover, many medical facilities now practice virtual surgical planning (VSP; also called surgical design and simulation, or SDS). In VSP procedures, patient information (such as a CT scan) is utilized to create a three-dimensional digital model of the patient's anatomy. Using this model, surgeons define the surgical approach and required supporting operative tools (e.g., cutting guides, fixtures, and so forth) in collaboration with AM technologists. Those technologists, who may belong to a dedicated applications team within a specific AM firm or be retained hospital staff, then convert the digital patient anatomy into one or several dimensionally precise physical models using AM. This model is used to corroborate the dimensional accuracy of additional, AM-produced, bespoke surgical tools, designed for the individual patient and operative pathway and for surgeons to practice the surgical approach using a corporeal facsimile of the patient. For example, the Alberta Reconstructive Technique (ART), which involves the intentional use of VSP and AM-produced surgical tools for jaw reconstructive surgery, has been demonstrated to yield statistically significant clinical outcomes, including a reduction in patient mean rehabilitation time from 73.1 months to 21.4 months, representing a patient gain of 1.9 quality-adjusted life-years.

AM is particularly well-suited to clinical practice: since medical interventions must be tailored to the individual physiology, anatomy, and context of the patient, AM's intrinsic flexibility lends itself to medical applications. The use of AM for prostheses and other devices, for example, has grown considerably. The NIH now hosts a repository of printable prosthetic devices, and several start-ups and volunteer organizations have emerged that focus on scalable, AM-enabled prosthetic devices.

It is thus safe to conclude that AM will be used heavily in clinical practice over the coming decades. New advances in AM at the intersection of digital design and biomechanical engineering will enable novel interventions—such as femoral stems that incorporate lattice structures to reduce stiffness and improve patient outcomes. Giannopoulous and colleagues, writing in *Nature,* summarize the use of AM in cardiovascular medicine as follows:

> [AM] technology has been used in practically the entire range of structural, valvular, and congenital heart diseases, and the added-value of 3D printing is established. Patient-specific implants and custom-made devices can be designed, produced, and tested, thus opening new horizons in personalized patient care and cardiovascular research. Physicians and trainees can better elucidate anatomical abnormalities with the use of 3D-printed models, and communication with patients is markedly improved. Cardiovascular 3D bioprinting and molecular 3D printing, although currently not translated into clinical practice, hold revolutionary potential. 3D printing is expected to have a broad influence in cardiovascular care, and will prove pivotal for the future generation of cardiovascular imagers and care providers.

Beyond direct medical interventions, AM may be used to maintain hospital operations, especially in geographically remote or underserved locations. A review of eight rural care facilities in Kenya found that AM could be utilized to bridge gaps when lead times are unacceptable for traditionally supplied components, as well as to fulfill spare parts for worn equipment. In future, the use of 3D printing (especially in surgical practice and patient-physician engagement) could be indistinguishable from routine clinical practice. The incorporation of AM equipment within or highly proximate to the clinical setting may broaden the range of patients for whom customized treatment pathways utilizing AM can be made available; already, collaborations between hospital networks and medical teaching universities with AM facilities are becoming more common. Moreover, AM may be used to accelerate the introduction of novel medical interventions in specific adverse scenarios; for example, in response to COVID-19, AM was deployed in a variety of contexts—such as in the fabrication of personal protective equipment, ventilator components and accessories, and consumer products meant to minimize the risk of accidental infection.

Of course, each AM-enabled future for medical devices is equally associated with potential risks. For load-bearing implanted devices, AM components must be rigorously scrutinized to ensure that the devices do not fail in use or invoke unexpected adverse effects in patients. As such, the maturation of these applications will remain beholden to the development of standardized practices by professional societies, work that will increase confidence in the use of AM for medical interventions. In the case of rapid fulfillment of spare parts using AM, the warranty and device performance issues already discussed are even more important (while it can be inconvenient for a consumer appliance to malfunction, the consequences of a malfunctioning life-support device may be fatal). Finally, the intersection of AM and medicine raises new skill requirements for prospective AM technologists: if AM systems are incorporated into the physical infrastructure of care facilities, what skills and knowledge must new employees possess to operate these machines at a high level of precision? And, if an AM-produced device is associated with an adverse effect, who is ultimately liable? While AM has cemented itself as a critical enabling technology for advanced medicine, there remain significant practical challenges associated with reaching the technology's full potential.

AUTOMOTIVE

AM has been used for decades in the prototyping of automotive components, but the technology has only recently been incorporated into end-use components. Currently, the cost premiums associated with AM limit its utility for mass-market vehicles; pioneering use-cases of AM for primary production have been limited to specific luxury vehicles (e.g., the Bugatti Chiron, BMW i8 Roadster, etc.). These "lighthouse" demonstrations of AM in performance automotive are laying a foundation of technical competency for further application development in this sector. Moreover, we believe that the automotive sector's utilization of AM reflects a microcosm of AM's general utility and trajectory across the manufacturing sector more broadly.

The automotive sector represents perhaps the best illustration of AM's impact across the product lifecycle. From first concept, physical prototyping of new component or product introductions is integral to the development process. Prototypes are used to validate component characteristics, define system-level interactions, identify failure mechanisms to be addressed, and communicate design intent and project feasibility to customers and senior management. Additionally, robust physical prototypes are necessary to validate device performance for the purposes of regulatory review and compliance; it is not an overstatement to say that dimensionally and mechanically accurate prototypes are a prerequisite to the realization of new product introductions in the automotive sector. To that end, the use of AM for rapid prototyping is significant and growing. Giffi and colleagues (2014) argue that the use of AM for prototyping offers four distinct competitive advantages over conventional prototype fabrication: (1) AM enables greater exploration of the early design space for new component introductions insofar as multiple product permutations may be fabricated at relatively low marginal cost per permutation due to the absence of part-specific tooling; (2) AM may enable greater quality by facilitating a greater range of physical performance tests and reducing the reliance on virtual prototyping and engineering activities; (3) AM can be used to produce customized tooling at comparatively lower cost than conventionally fabricated tooling—such tools have been empirically demonstrated to increase productivity and reduce time to market; (4) AM reduces the cost of tooling in product design, even when AM is not chosen as a primary production method: insofar as geometric design changes may propagate inefficiencies by requiring downstream processes (such as tooling design) to be reworked, AM prototypes enable flexibility in early product design without the associated encumbrance of tooling. The authors reference an example from Ford, comparing a typical prototyping cost and time of $500,000 and four months with an AM counterpart, which cost $3,000 and was iterated upon in the span of days. Many of the arguments that

Giffi and colleagues make resonate with the themes of our own research, which finds AM provides greater early design-space exploration, reduces the criticality of virtual engineering workflows (shifting them to physical testing and prototyping), and minimizes the associated costs of engineering changes throughout the development process. We consider strongly the possibility that when components can be reasonably prototyped using AM (i.e., the AM component will represent a suitable demonstration for the purpose of system-level analysis or mechanical testing), automakers will have a strong incentive to do so—even if the final production method will use a conventional process. In 2019, for example, representatives from BMW claimed that their AM facilities processed 30,000 prototype orders annually.

Beyond prototyping, AM has been demonstrated to augment productivity throughout the production workflow. Jigs and fixtures can be designed, fabricated, tested, and iterated upon within the span of several days, rather than the weeks needed for these production aids to be fabricated by machining and assembly. In some cases, production tools may be customized to the individual operator, reducing variability in production tasks while maintaining ergonomic comfort. Co-location of AM machinery proximate to production tasks enables low-level operators and assembly technicians to identify and realize solutions to specific challenges during production activities quickly and with greater ownership.

Aftermarket, AM has been used for the fulfillment of legacy components—especially for vehicles long out of production, such as vintage vehicles as well as utility vehicles with long operational lifetimes. Mercedes-Daimler, for example, was one of the first to announce the AM production of metal spare parts, using AM for its Unimog trucks in early 2017. Spare parts fulfillment, as we have described previously, opens new horizons for firms to deliver service at reduced operational cost. Given that AM systems are not bound to specific geometries, a single machine can produce a wide variety of parts on demand. Automakers may then shift from physically warehousing spare parts to just-in-time production. In 2016, BMW speculated on a fulfillment model where AM systems were co-located with repair facilities and in-house engineers would fulfill spare parts requests based on customer inquiries in nearly real time. Thus, while the automotive sector has been historically outpaced in its use of AM by other industries, it is safe to say that it is catching up. The advantages of AM we have elucidated thus far in this sector are, notably, not unique to the production of automotive vehicles. Rather, it is inarguably the case that manufacturing generally will identify these same advantages and utilize AM to improve design workflows, customer service, and net productivity. In this regard, we consider the automotive sector as a useful proxy for the general maturation of AM writ large and believe that specific advancements in the use of AM for the direct production of end-use components will largely be driven by this sector. It is further important to emphasize that advancements in the use of AM for the automotive industry will necessarily result in increased market traction for these technologies. Successful technology demonstrations are likely to engender greater confidence in other industries, compel the automotive supply chain to onboard AM capabilities to retain competitive positioning, and upskill a new generation of AM-equipped workers.

With this in mind, it would be premature to say that AM is a fully mature technology for mass-market applications; as we have argued, cost premiums associated with AM continue to limit the potential of the technology to penetrate high-volume applications. Though such costs may be overcome, they require firms to optimize individual components and assemblies to realize the advantages of AM—namely, shape-optimization and part consolidation—as well as to master the relationship between component design and production strategy to minimize the cost of AM production.

It is a testament to AM's strong industrial potential that automakers persist in marking large, targeted investments in the technology. Rather than play fast-follower, automakers continue to compete with one another to demonstrate new applications of AM, including those that unlock new modes of customer value. Ford, for example, discussed the use of sound patterns unique to the customer to create bespoke geometries for the bitting of lock-and-key combinations used for the nuts that fasten tires to the vehicle. Though a niche application, this is an early demonstration of AM's potential to enable new vectors for value delivery by integrating customer-specific preferences or characteristics into component design. In mid-2020, BMW announced a new campus in Munich, Germany, dedicated to AM research, development, and pilot production. Automakers General Motors and Volkswagen have participated strongly in consortia and other partnerships (including our own at MIT) focused on the advancement of AM technologies. As new mobility futures emerge—including increased vehicle electrification and new models of shared mobility—the automotive industry must rethink the fundamental design of automotive transport, and especially passenger transport vehicles. AM's technological advantages may first justify its use in new vehicular architectures, such as performance-optimized electric powertrain components, and later find its way into aesthetic applications that enable new modes of value delivery for manufacturers and vehicle operators.

While the automotive sector represents an immense opportunity, it is clear that the full promise of AM has yet to be fulfilled. Over the long term, the maturation of AM processes will require new advances in materials, machinery, and production workflows that meet the rigorous operational constraints and cost minimums of the automotive industry. In the near term, however, firms that seek to maximize the use of AM must continue to invest in a skilled and experienced workforce in order to overcome specific operational hurdles associated with new application development.

Policy Recommendations

All in all, AM has tremendous potential to augment domestic manufacturing competitiveness, reshape domestic and global supply chains, and introduce new generations of products and business models to the marketplace. Nevertheless, the rate of technology adoption is ultimately limited both by intrinsic (i.e., technological) and extrinsic (i.e., standards development, workforce availability) market forces. To conclude, we propose several principles that could guide policy options for accelerating the technology's growth and adoption across the industrial landscape.

1. **Invest in the full spectrum of basic AM research that can be applied to commercialization.** Resources dedicated to the advancement of AM technologies often exist at extreme ends of the research spectrum, with academia concerned with basic research (e.g., new technology invention and concept demonstration), and professional bodies concerned with applied research (e.g., the development of standardized workflows and test procedures). Between these two extremes exists a span of research and commercialization activities that can accelerate the development of basic research and its deployment into new commercial ventures and inventions that support the maturation of the industry at a grand scale. One may consider the various intermediary steps in an AM production workflow—from software to post-processing—as windows of opportunity for additional research. New systems and methods that streamline the AM workflow (e.g., those that automate the removal of support material) will facilitate the technology's introduction at all levels, and development of instrumentation and algorithms for quality control is essential. Arguably, private investment to date has been dominated by large, well-capitalized firms in major industries (e.g., aerospace) that drive research to support those firms' needs (e.g., the qualification of specific alloys for use in AM systems). Government may play a role in facilitating fellowship programs, like the ACTIVATE program (itself a spin-out of the Lawrence Berkeley National Laboratory), which aim to derisk commercialization of new technologies, and provide support to talented entrepreneurs. Further, support for process, materials, and data standards must consider the interoperability between AM technology and adjacent processes and systems. Support for dissemination and archiving of shared knowledge – facilitated via open data repositories, process documentation, and so forth – in specific industry segments in concert with appropriate regulatory bodies – can encourage further encourage adoption of AM. Government is, arguably, uniquely positioned to play the role of aggregator insofar as it does not have the strong commercial incentive felt by industry to retain process knowledge for commercial benefit.
2. **Support small- and medium-sized enterprises to develop AM capacity and expertise.** Given the present economics of AM, and the limited supply of skilled workers to fill AM roles, the distribution of advanced users of AM remains concentrated among large, well-capitalized multinational firms—especially in the aerospace, automotive, and medical device industries. This allocation of technology capability is, arguably, inefficient and weakening to U.S. manufacturing competitiveness insofar as AM's potential spans the product lifecycle and can be introduced (when a skilled workforce is available) at relatively low cost through the use of third-party production partners. Supporting architectures to cultivate and grow workforce and institutional capabilities for small- and medium-sized firms will be necessary to overcome the present utilization gap and democratize the use of AM across the manufacturing landscape. Training programs housed in Manufacturing Extension Partnership centers, for example, might prove effective in

upskilling workers within small and midsized firms and facilitate the democratization of AM implementation. The government is well-suited to providing incentive programs to override the risk-driven skepticism of those disinterested, at present, in utilizing AM technologies. Such incentive programs would allow firms to explore AM's use without significant operational risk, justifying a value-driven investigation of AM technology for transforming their products or production processes. Government—especially at the State and regional level—may further seek to support small- and medium-sized enterprises through development of shared AM infrastructure. Facilities established by government that provide industry access without requiring significant capital investment may serve as hubs for the coordination of workforce programs and new technology demonstrations, or even as pilot factories that implement AM and advanced automation at scale.

3. **Support the development of high-quality, workforce-oriented training programs at all levels.** A limited supply of qualified workers to constitute a robust AM labor force—both in operations and in design and engineering roles—is broadly considered to be a critical challenge limiting the rate of adoption of AM technologies. Moreover, labor displacement in manufacturing is well-evidenced, especially for low-skilled or low-education workers. Upskilling programs can serve the dual purposes of advancing the industrial use of AM while retaining experienced manufacturing workers.

4. **Accelerate approaches to open innovation with AM as a fulcrum.** The COVID-19 public health emergency demonstrated that there are sizable communities capable of rapidly creating new products or addressing supply-chain disruptions using flexible manufacturing, a capacity that includes but is not limited to AM. But, the unfamiliarity and perception of risk associated with these initiatives may curtail their potential impact over the long term. Moreover, the success of these efforts was hamstrung by a lack of a supporting infrastructure to identify and accelerate the most promising ideas. Government bodies ought to create formal mechanisms for identifying and supporting communities whose ideas may be instrumental to the development and commercialization of new innovations, accelerated by AM. One example worthy of further exploration was the partnership between the NIH, America Makes, and the Department of Veterans Affairs focused on AM-enabled production of personal protective equipment. Government agencies are uniquely equipped to help these types of communities support other categories of products or innovations (e.g., departments of transportation may organize communities focused on infrastructure applications). Given government's regulatory authority (both through formal rules and through informal association or oversight with various professional bodies) and purchasing power, it is well-suited to facilitate the centralization and acceleration of innovative ideas. Such an exchange may be dual-purposed, where value is created for innovators through government-provided resources (e.g., incentive schemes to encourage participation) and also designed to develop internal technical competency and understanding within the government.

5. **Understand and proactively combat the prospective risks of intellectual property piracy, counterfeiting, and reverse engineering through secure and effective file-sharing standards.** The control

and transfer of digital information is paramount to the operation of AM processes and especially to the execution of AM-enabled distributed production networks. However, standardized data management and file encryption protocols remain laggard, inviting considerable risk that may prevent AM from reaching its full potential. The digitization of production requires a commensurate maturation in the management of data to ensure that new production workflows cannot be intentionally disrupted. Of equal importance, such protocols will be necessary to increase industrial confidence and enable further applications of AM in defense-critical arenas and across multinational, highly competitive firms.

6. **Define through legislation the ownership of digital information and outline concretely the boundaries between consumer and manufacturer rights and entitlements for device repair.** AM provides skilled home users, as well as third-party repair shops, with the ability to more capably repair their own products. At the same time, OEMs are increasingly wary of consumer- and third-party-driven repair activities, in part (though, importantly, not in whole) as a mechanism for financial capture at the expense of the consumer. The convergence of high-fidelity geometry reconstruction using scanning tools, the trend against home and third-party repair, a lagging intellectual property regime not suited to digital fabrication, and increasingly skilled customers with increasingly capable machinery, poses significant legal challenges and creates nebulous “gray-areas” related to repair activities. It is prudent for government to preemptively clarify these boundaries through legislation rather than adjudicate these issues using jurisprudence constructed for different types of property in a different era.

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Endnotes

1 The term "AM," used preferentially throughout, commonly refers to the end-to-end process of creating a finished component using 3D printing as the primary forming step. The industry's use of AM as the overall term also indicates the maturation of 3D printing technologies for manufacturing-related use cases.

2 The bounding box dimensions of the part are (X,Y,Z) = (75, 50, 12.5) mm; XY is the horizontal plane.

3 Complexity is defined as $C = \left(1 - \frac{V_p}{V_b}\right) + \left(1 - \frac{A_s}{A_p}\right) + \left(1 - \frac{1}{\sqrt{1+N_c}}\right)$, where V_p=Part volume, V_b=Bounding box volume, A_s=Surface area of a sphere with part equivalent volume, V_p=Part surface area, V_p=Number of holes/cores within the part (Conner et. al, 2014).

4 The quoted tolerances of the CNC machined parts are ±0.13 mm for Bureaus 1 and 2. The quoted tolerances of the SLM parts are ±0.076 mm for Bureau 1 and ±0.076 mm for the first 25 mm plus ±0.051 mm for each successive 25 mm dimension for Bureau 2.

5 The bounding box dimensions of the part are (X,Y,Z) = (75, 50, 10) mm; XY is the horizontal plane.

6 Unless stated otherwise, data is taken from the Bureau of Labor Statistics' Job Openings and Labor Turnover Survey, which can be accessed at https://www.bls.gov/jlt/.