SECURITY 2040

ADDITIVE MANUFACTURING IN 2040

Powerful Enabler Disruptive Threat

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Perspective
EXPERT INSIGHTS ON A TIMELY POLICY ISSUE

RAND CORPORATION

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A*dditive manufacturing* (AM) describes types of advanced manufacturing that are used to create three-dimensional structures out of plastics, metals, polymers, and other materials that can be sprayed through a nozzle or aggregated in a vat.[1] These constructs are added layer by layer in real time based on a digital design. The simplicity and low cost of AM machines, combined with the scope of their potential creations, could profoundly alter global and local economies and affect international security. The following speculative narrative describes some of the potential security implications of this emerging technology.

> In August 2039, the U.S. cell of a radical group from a South Asian megacity hatches a plan to force the United States to pay attention to its plight. The South Asian country had once been a mecca for low-cost manufacturing. Its rock-bottom labor costs and favorable maritime location had attracted Western and Chinese companies for decades. And while it continues to produce the most inexpensive garments and mass-produced items, it has seen unemployment in manufacturing jobs rise to 55 percent as factories that once assembled more-specialized goods have been replaced by local AM printers in the markets to which those goods were once exported. Meanwhile, rising oceans threaten the 12 million people trapped in the megacity as the low-lying surrounding lands are flooded much of the year. The United States and Europe refuse to admit the shiploads of emigrants attempting entry each week. Desperate radical cell leaders based in San Francisco decide to attack the U.S. Coast Guard and Navy ships that are preventing their countrymen from landing at the newly recommissioned and vastly expanded immigration and refugee facilities. They use a large printer and advanced design templates purchased on the Dark Web to manufacture dozens of aerial and underwater drones carrying improvised explosives.

Obtaining some of the required materials is a challenge, but they have no shortage of technical expertise: Many in the megacity are now engaged in AM of everything from circuits and small electronics to custom prosthetics and even human organs. The first gun was printed back in 2013 (Walther, 2015; Greenberg, 2013); by May 2017, researchers at the U.S. Army Armament Research, Development, and Engineering Center had successfully designed, printed, and fired a grenade launcher (Hodgkins, 2017). After downloading free designs from the web, the terrorists begin printing a multitude of swarming unmanned drones.

Such a bleak future scenario might not be likely in 2040, but the vignette illustrates how the increasing access to and capabilities of AM have the potential to dramatically disrupt the prevailing state system and international order. The possible transformation has been compared with the jarring effects of the Industrial Revolution and the emergence of economies of scale in the 18th and 19th centuries.[2] These earlier changes in manufacturing ushered in a new economic era and drove military industrialization, transforming warfare at a catastrophic cost to humanity while simultaneously bringing about incalculable benefits. Once mature, AM could play a role in reducing employment when coupled with artificial intelligence (AI) and automation, changing the balance of power between developed and developing nations, and reshaping global trade. It will not only exacerbate many of today's most pressing socioeconomic challenges but also unleash new kinds of security threats.

Some of the security implications are not difficult to imagine. As it becomes easier and cheaper to print weapons, the threat of kinetic attacks (i.e., violence through lethal force) could grow significantly.[3] Through the internet, foreign terrorists and other violent extremists will likely have ready access to printable designs of new and more-dangerous weapons. AM will also make it easier for homegrown dissidents and "lone wolves" to print weapons quickly in locations where they previously would not have had access to them (e.g., schools, government buildings, airports). Even these secure sites might be vulnerable to insider threats if a would-be attacker can access an AM printer and the internet.

Other security threats are more diffuse and could be more difficult to monitor or effectively counter. Consider, for example, the potential relationship between AM and cyber. In 2017, small-scale and nonstate cyberattacks were typically nonkinetic events (e.g., hacking an online vendor's sensitive customer information). The hacked information was then sold for a profit or used to commit fraud. But with AM, the stakes of cyberwarfare could increase. Hackers might not stop at just stealing personal or financial information but go on to gain access to designs for sensitive technologies. With access to a printer, a hacker might be able to reproduce homemade jamming technology and disrupt surveillance, compounding the threat of cybersabotage. This threat is especially severe if hackers are able to introduce design flaws into critical parts (such as an airplane fuselage or an autonomous car) by infiltrating a printer or corrupting digital designs. As digital designs are increasingly embodied in physical things, these attacks will begin to have real-world consequences beyond the digital space and will increasingly blur the lines between kinetic and nonkinetic threats.

Along with weapon proliferation and cyberwarfare, AM has the potential to disrupt economies and the prevailing international order. Like the jarring effects of the Industrial Revolution before it, AM could upend traditional economies of scale while making highly customizable and complex products widely available to consumers. It also might allow nonstate actors to develop items that previously required expertise and industrial capabilities exclusive to more-advanced states. While it is still not clear how many and which types of products will be additively manufactured in the future, the proliferation of AM machines, ready access to raw materials, and the free flow of digital plans—coupled with automation and AI—could profoundly alter the global economy, international security, and the organization of society (Campbell and Ivanova, 2013).

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By decentralizing manufacturing, individuals and firms might choose to produce locally, weakening the tie between consumption and globalization that currently connects disparate parts of the globe through complex, multicountry supply chains.[4] Digital technologies, service-based industries, and intellectual property (IP) resources could become increasingly important, displacing traditional manufacturing and labor across an ever greater number of industries.[5] In particular, rapid prototyping, along with the creation of highly specific and technical parts (such as aircraft machinery or vehicle mirror fittings) are orders of magnitude faster and cheaper than traditional manufacturing methods. Many experts believe that these forces will cause profound disruptions to the current economic order. For example, Oliver Cann, writing at the World Economic Forum, estimates that there will be a net loss of more than 5 million jobs in 15 major developed and emerging economies over the next five years because of the "Fourth Industrial Revolution" (which includes AI and machine-learning, robotics, nanotechnology, AM, and genetics and biotechnology) (Cann, 2016). Raoul Leering, head of international trade analysis at ING, predicts that AM will be even more disruptive by 2060 and suggests that the technology alone could wipe out almost one-quarter of cross-border trade by that date (Leering, 2017).[6]

Although the technical aspects of AM have been slowly improving over the past 30 years, the development of printed weapons and the widespread commercialization of AM technology are indicative of possible security threats. This technology has the potential to improve efficiency while increasing product customization and reducing waste. Much has been written about the promise of AM and the societal benefits that it will bring. However, as with any transformative technology, its potential to cause harm must be carefully considered and mitigated or prevented if possible. Given the growing interest in the disruptive potential of AM, this Perspective explores the possible negative impacts of this technology, specifically focused on security in the year 2040.

To better anticipate likely futures and inform policymakers today, this Perspective focuses on the most-consequential implications of AM technology for 21st-century security. We explore the threat environment in 2040 and ask two basic questions:

1. What are the varying implications of these potential futures on personal security, domestic stability, and international order?
2. What strategies can policymakers use today to shape this future trajectory?

Our framework on the disruptive dimensions of AM identifies the sectors that could become the greatest security challenges, and it might help policymakers navigate this new policy and regulatory domain.

To gain insight into these two questions, we used a combination of analytic techniques and insights from multiple disciplines. We began by exploring the existing literature on AM, including current and future trends. We then interviewed top experts and industry leaders in a variety of AM industries and related fields of research. We developed a semistructured interview protocol for face-to-face, phone, and email-based interviews. (A full list of the questions can be found in the appendix.) We identified interview subjects from web searches and trade publications and used snowball sampling techniques to expand our pool. These interviews helped us not only identify emerging trends in the field but also understand the attitudes, beliefs, and perceptions of industry leaders. During the interviews, along with general industry questions, we asked our subjects to speculate on the security implications of AM in 2040. Eleven interviews were conducted between March and August of 2017.[7]

These questions helped shape a subsequent workshop with 25 experts from varied backgrounds—including industry representatives, U.S. government and military personnel, and RAND national security researchers. The workshop, conducted in May 2017, explored security threats in 2040 and strategies for mitigating them. Breakout groups of four or five people discussed different potential threats.[8] Each group was asked to identify the assumptions, events, and necessary conditions that would give rise to different futures and consider the distinct security threats these futures might entail. They were also asked to suggest early-warning signals that might indicate movement toward each of these futures, as well as concomitant hedging or shaping actions for policymakers to limit effects on future security.

In the rest of this document, we first provide a brief overview of current trends in AM and possible future trajectories of the technology. Drawing on this background, we then identify the industries expected to be most disrupted by AM. This technology's proliferation will disrupt some companies and sectors more than others, with important implications for producers and consumers alike. After mapping the dimensions of commercial disruption, we then discuss how AM could introduce new threats and security challenges. Based on our interviews and the expert workshop, we have identified two areas that should be of particular concern for policymakers: (1) weapon proliferation and (2) economic dislocation. We describe how AM could contribute to these future threats and discuss specific measures that policymakers could take to prevent and mitigate them. Ultimately, we argue that the general public and policymakers must recognize that these threats cannot be fully prevented. The proliferation of AM will bring with it both incredible benefits and new risks.

The Future of Additive Manufacturing

This brief overview of AM and discussion of its future trajectory provide the basic background necessary for subsequent sections. As such, this material is not intended to be comprehensive.

History of AM

Initially developed in the 1980s, AM has seen an explosion in interest recently across various sectors. Near-term applications of AM include clothing, medicine and biomedical technology, large-scale construction, electronics, computers, food, weapons, and military products. These applications include everything from AM manufactured soles for Adidas shoes to replacement parts for nuclear weapons and the International Space Station. The simplicity and decreasing cost of AM machines, combined with the scope of their potential creations, has just begun to make this technology a useful tool for many industries. If or when these machines or their products will be found in most households and become a part of everyday life remains to be seen.

AM comprises a variety of processes used to create three-dimensional structures out of various materials. Prior to 2009, the majority of AM printers were used industrially. In the past decade, however, many of the patents on critical parts of this technology expired. Once prices began to drop, the use of these machines expanded to a variety of industries for multiple purposes.[9] The machines also became popular among artists and creative tinkerers. "Fablabs" (fabrication laboratories) and "maker-spaces," which provided physical locations and machines for individuals to fashion their own creations using AM and other advanced technologies, sprang up in major cities. Their number increased 14-fold between 2006 and 2016, to approximately 1,400 worldwide (Lou and Peek, 2016).

Industry experts often cite the progression of the market for fax machines and then two-dimensional printers—from industrial use to neighborhood shop locations and finally into the home—as a model for how they believe the market for AM printers will evolve. They note that an AM printer in every home seems as likely today as home-based inkjet 2D printers would have seemed to someone living in the mid-1980s.[10] Other experts are more skeptical, suggesting that AM printers will likely be used in neighborhood maker-spaces but not owned in large numbers by consumers. Another possibility is that individuals will have relatively inexpensive AM printers with a small number of raw materials for relatively simple jobs and will use more-advanced machines in central community hubs for complex items.[11]

In traditional manufacturing, the cost of production increases based on how complicated an object's shape is. On an AM printer, costs are roughly the same for producing complex objects and simple ones. Fabricating an ornate and complicated shape does not require more time, skill, or cost than printing a simple block, once the digital design is completed. Industry participants refer to this as getting "complexity for free." Moreover, AM allows for creation of objects that cannot be built using traditional methods. Through digital design and layered construction, the input requirements are nearly the same to print a solid block of some material as they are to print an intricate fractal structure that cannot be made at all through traditional, or "subtractive," manufacturing.

As we will discuss further, AM machines could soon be able to replicate themselves, with organizations such as RepRap and Fab@home providing freely available open-source schematics on how to manufacture the necessary parts. One machine would then have the potential to produce an indeterminate number of others that can be repaired indefinitely as long as raw materials are available.

Financially, the AM industry grew by nearly 26 percent in 2015 and surpassed the $5.1 billion mark in 2016 (Wohlers Associates, 2016). Compared with other, more-developed fields—such as bio-

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tech, which grew by only 5 percent in 2015 (Ernst and Young Global Limited, 2016)—AM has not yet matured and continues to see dramatic growth rates. In an online survey of 120 U.S. manufacturing professionals in 2015, 71 percent reported using AM in their production, for either prototyping or finalized goods. Further, 52 percent of manufacturers predicted that AM would be used for "high-volume production" in the next three to five years (PwC and The Manufacturing Institute, 2016). According to one of our interview participants, "Every major corporation on the planet has invested [in AM]. We will see huge disruption. The automotive industry is already being disrupted. 3D printing is done very exactly with a computer—older methods could not hit the same geometries. . . . 3D printing can make things that cannot be made any other way." Notwithstanding this optimism, some industries or sectors will be more disrupted than others. By exploring future trends, we hope to better understand variation across sectors and the implications for security threats.

Current and Future Trends

AM has begun to be adopted by legacy industries, shifted some production practices, and created new businesses. AM technology and expertise can be found in many countries across the world, including the United States, Germany, China, India, South Africa, Taiwan, and Iran (Fey, 2017). The industry will undoubtedly continue to develop worldwide over the next few decades, and the abilities of the printers will be vastly different than they are today in ways that are not completely predictable (Wong and Hernandez, 2012). Notwithstanding this potential, it is still unclear how many goods will eventually be substituted with products fashioned from AM. Emerging trends suggest that AM might not rely on traditional supply chains to the same extent that subtractive manufacturing does. Other trends, such as printers that source their materials from locally available resources—including by recycling plastics from such items as milk cartons and, eventually, using regolith (or "moon dust")—indicate that a minimal initial investment could result in nearly complete individual autonomy.[12]

Many of the current trends in AM will shape the future of the technology and will determine which aspects will be the most disruptive to manufacturing, the economy, and global security as the world approaches 2040. We briefly explore these trends and speculate on their future trajectories.

Printing with Multiple Materials

Historically, AM machines could only print with one material at a time. This constraint limited the types of products that could be generated. Objects with multiple material components require more time and energy to assemble. Newer machines, however, have the capacity to print with multiple materials simultaneously. This will allow printers to produce a wider variety of complex and composite objects and to do so more quickly. In the short term, these items will begin to include electrical circuits, potentially enabling the printing of devices that are ready to use right off the printer—capabilities that are now being explored. Scientists are also further developing the printing of human tissues, potentially permitting the creation of complex custom-built organs that can be transplanted with lower risk of rejection.

One industry expert whom we interviewed described how, in 20 years, his organization will "make graded material products that change from one material to another. We will be able to put normally incompatible materials together." The expert went on to highlight the vast range of products that will be feasible using these mixed materials: "We can print electronics, insulators, conductors, plastic substrates all together without degradation. We will integrate devices into the structures." Such mixed-material products will have everyday benefits in applications like wearable biomedical technology, but they could also have security implications—for example, more-versatile nonmetal polymers and biological structures can help conceal weapons and make it more difficult to identify or detect threats.

Self-Duplication

Recently, open-source communities have emerged around AM and have developed printers that can generate nearly every part necessary for their own replication. Not all parts can be produced through AM yet, but significant improvements have been seen in the homemade production of electronics and motors. Once these pieces become reproducible and readily accessible to hobbyists, point-of-sale controls will not be able to limit (or even track) the proliferation of AM printers. Such controls are widely used to regulate dangerous or risky goods (e.g., firearms, fertilizer, and some medications), but they would be far less effective with reproducible printers. Currently, the self-replicating capabilities of these printers remain limited, and demand is low. However, the implications of such a capability should not be underestimated, especially because some of the current technological challenges are already being addressed.

As replication becomes less costly, printing machines could become ubiquitous. Access to raw materials, energy, and blueprints will be the only limiting factors for the creation of a manufacturing sector. Self-duplication will dramatically increase the accessibility and range of AM, growing black-market sales and other aftermarket (i.e., secondary) opportunities. As do-it-yourself capabilities grow, it will be easier not only to print lifesaving medical devices in a jungle but also to produce a cache of weapons outside the reach of a state or other regulatory body.

Size and Scaling

Today, most AM printers can only produce small objects. Although industrial printers can be quite large, most home-use machines are small enough to fit on a desk. When large objects are built in segments, the weakness in joints and bonds reduces strength or durability. Larger printers are being designed and built to overcome this limitation. In March 2017, a San Francisco company produced a house using AM in less than 24 hours (Moon, 2017). That same month, a construction company in Dubai announced plans to build an AM-produced skyscraper (Sulleyman, 2017). Such scaling capabilities also might be attractive to terrorists, helping nonstate actors develop larger weapons (e.g., aircraft, missiles) that previously required expertise and industrial capabilities exclusive to more-advanced states.

AM machines also might be able to create scaled versions of their own parts, thus leading to smaller printers with more-precise capabilities. The most-precise printers now can print at a resolution of 0.01 millimeters, or 10 microns (Paulsen et al., 2012; Utela et al., 2008; Wohlers and Gornet, 2016). Future printers might be useful for making smaller electronics and circuitry, precision mechanisms, and other miniature-scale endeavors. These advances could have important implications for the next generation of computers.

Sourcing of Materials

The growing flexibility and replicability of printers suggest the potential of AM. And if current trends continue, today's technological constraints might be negligible in a few decades. Similarly, the material constraints of AM are becoming less binding through time. The raw materials currently used in AM are expensive, and their sourcing remains an important focus of ongoing research and development. Some researchers are working on methods to incorporate locally sourced or recycled materials and dramatically reduce costs—experimenting with reusing recycled plastic waste; generating plastics from plant-based cellulose; and printing with sand, glass, and clay. As more objects are made from locally sourced materials, there will be less reliance on current supply chains.

Of course, rare and nonsubstitutable minerals will still need to be transported, and these could continue to drive future costs.[13] But as the constraint on material types relaxes, more products will be produced locally, loosening the tie between everyday consumption and concentrated markets and potentially disrupting traditional economic forces. Admittedly, given the historic trend of declining transportation costs, not all products will become locally produced. Unless energy costs rise dramatically, many commodity products will continue to be produced remotely and shipped to consumer markets. However, the overall trend toward more additively manufactured, locally produced goods is likely to grow.

The benefits that localized sourcing and manufacturing could provide to violent extremist organizations (VEOs) are especially concerning. VEOs, such as Al Qaeda, tend to operate from remote areas outside the reach of state authorities. Such locations provide cover but increase transaction costs, making it harder to maintain supplies or build up capabilities. Local sourcing of materials could change this dynamic, mitigating one of the few advantages that traditional state security forces hold in their battle against VEOs. While it might not become any easier to acquire rare materials (e.g., radioactive elements), most weapons do not require such exotic ingredients.

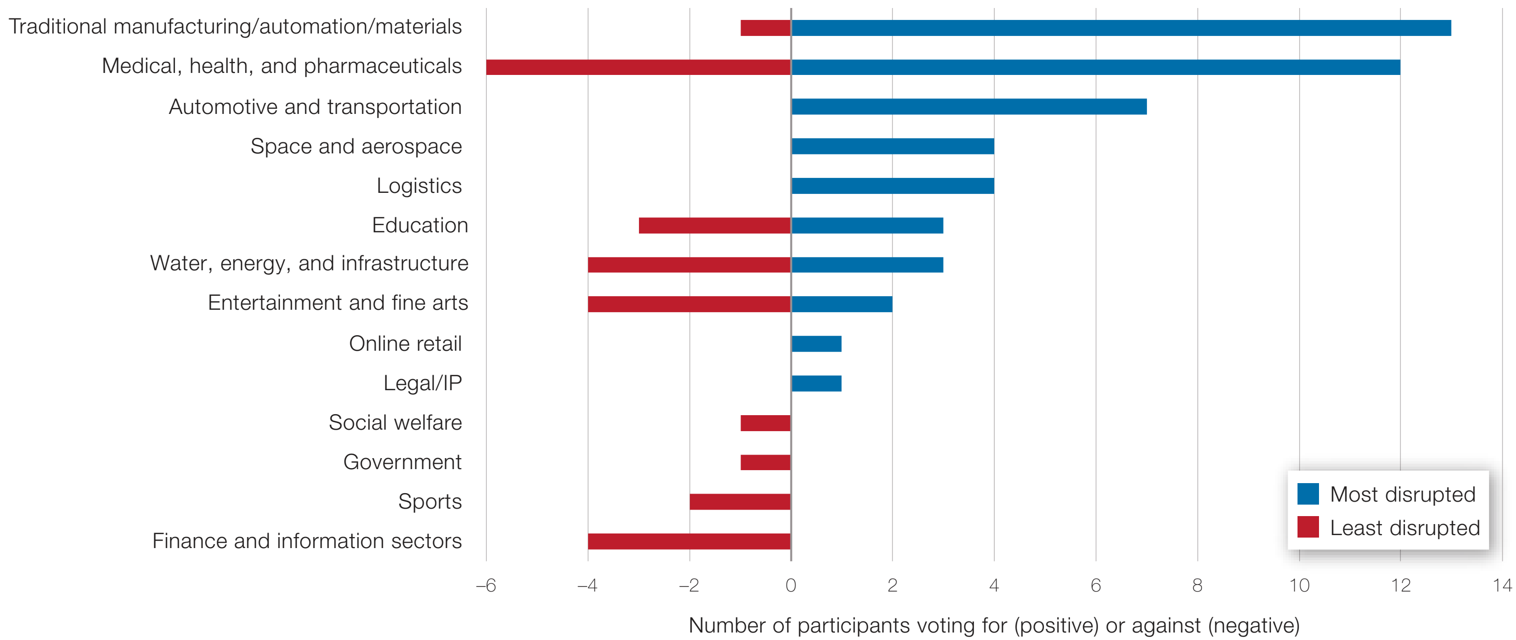
Dimensions of Disruption and Industry Impacts

The use of AM within various industries, both traditional manufacturing and more niche applications, has grown dramatically in recent years. However, not all industries and products will be equally affected. Despite some optimists' predictions that AM will become ubiquitous, the benefits and costs of this technology will likely vary widely across sectors. Eventually, some products could be entirely produced through AM, radically transforming these industries, but others might remain fairly constant as traditional manufacturing methods continue to dominate in price and quality.

Such uncertainty was evident in our expert workshop. We asked participants to list the industries they expected to be the least and most disrupted by AM. The diversity of responses can be seen in Figure 1. While some industries or sectors garnered significant consensus (e.g., manufacturing, logistics, and space were all expected to be on the high end of disruption), others were far more controversial.

Health, for example, is a complicated sector. Some workshop participants highlighted the far-reaching effects that AM might have

Figure 1. Expert Opinions on AM's Disruptive Effects Across Industries



SOURCE: Participant responses from RAND workshop.[14]

on customized medical devices, tissues, or other health products. These views were echoed in some of our expert interviews, with one expert stating: "It will change how we treat diseases. It will be very easy to scoop out organs and replace them—it will change all the treatments we do. . . . The medical field will be transformed dramatically. . . . We will be able to print livers, or we can print pieces of arteries for heart surgery. . . . This is really going to help on the warfighting front; it'll save lives." Other experts and workshop participants, however, focused more on health services, such as the basic doctor-patient relationship, and felt that health care would change little with the advent of AM.

Similar to the views on health care, the issue of food production and consumption was also controversial. Many experts did not see much potential for AM to change the way people eat. Others thought the technology would be revolutionary. According to one, "Food production will change—we will be able to make protein sources for people. Livestock won't be needed. We can directly make protein sources instead of raising a living animal for over a year. . . . I won't be surprised if no one is eating livestock in the next 30 years. From an energy standpoint, it doesn't make sense to spend that much to get a pound of meat."

In general, participants predicted that service industries dominated by personal interaction (e.g., social welfare, parts of health care, and the delivery and pedagogy of education) would be especially resistant to AM and its disruptive effects. Industries dependent on person-to-person exchanges and arts and entertainment will not suffer the same degree of disruption as traditional manufacturing and its downstream sectors (e.g., transportation). Beyond this general trend, however, respondents identified few patterns to help us discern which industries would be most affected by AM.

The industry experts we spoke with also did not reach a consensus on the degree of disruption nor on the sectors that would be most affected. Our interviews with these experts yielded a wide range of opinions about what percentage of goods sold ten years from now would be produced using AM. Some respondents predicted only 5 percent of goods would be produced using AM—indicating relatively few sectors would dramatically change—while others predicted a number closer to 50 percent. When asked to project 20 years out, the estimates varied even more, from 5 percent to 90 percent. According to a published report by Leering of ING, "It is tricky to define the exact potential of 3D printing, but some experts expect a share of 50% in manufacturing over the next two decades" (Leering, 2017). The wide range of responses from those involved in the industry illustrates the high level of uncertainty about this emerging technology, even among experts.

The wide range of responses from those involved in the industry illustrates the high level of uncertainty about this emerging technology, even among experts.

To help capture the full disruptive potential of AM, it is critical that we better understand the conditions that make some industries and sectors more or less likely to use AM. Regardless of whether any given product (broadly defined) will transition into AM production largely depends on where that product falls in a region spanned by two primary dimensions: (1) complexity and (2) customization or scalability. Products that are complex, needed in remote locations, and/or highly customized will be the most likely to be produced by AM as the technology progresses. Together, these characteristics help capture the degree to which AM improves on traditional manufacturing methods for a given industry and to what extent we should expect this industry to experience significant disruption.

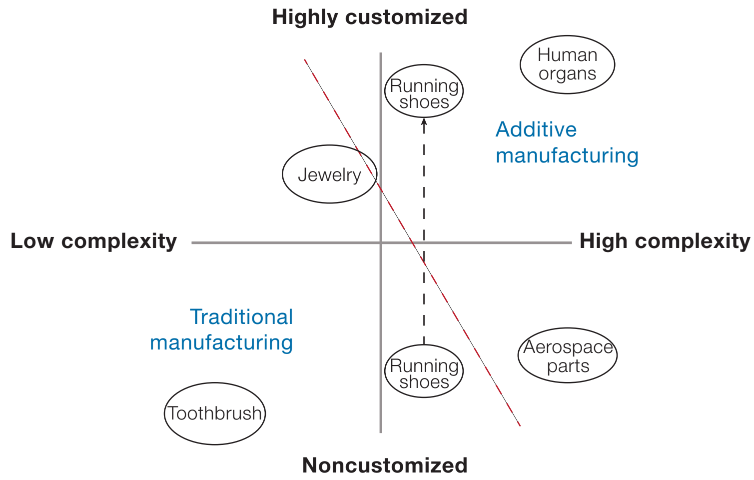
In addition to these primary dimensions of disruption, we also explored a related third dimension: accessibility (or distance). The relative benefits of AM also depend on the cost of securing a product or part, which can vary widely across areas that might be more or less remote. There is little reason to print a new product when it or its parts are readily available from nearby retailers, but AM is more valuable when access is restricted. For example, the National Aeronautics and Space Administration (NASA) has been experimenting with printing objects in space because "it can take months or even years, depending on the launch resupply schedule, to get equipment to space, and for exploration missions, resupply from Earth may be impossible" (NASA, 2014). In particular, NASA is looking into using printers on upcoming missions to Mars for which resupply will be difficult. Similarly, printers could be useful in combat environments where traditional supply chains cannot be supported; a printer with a range of raw materials could eliminate the need to maintain a large stock of parts.

Figure 2 offers a conceptual illustration of the two primary dimensions, complexity and customization, along with a few examples of products. The dashed line represents the current technological frontier of AM (i.e., the state of the art). This line is theoretical and purely illustrative. The area on the right side of the line represents industries or products that are susceptible to being (or have already been) disrupted by AM. The area on the left side of the line reflects the domain of traditional subtractive manufacturing. In practice, we cannot say exactly where the line exists today; conceptually, this figure can help us imagine the technology's future trajectory across different sectors.

Using current technology, traditional manufacturing is less expensive and remains the most cost-effective means of production for most goods, which largely fall to the left of the technological frontier as represented in Figure 2. Examples of such goods include simple and inexpensive commodities, such as toothbrushes. As the technology develops and material costs decrease, however, this frontier will move to the left, making AM cost-effective and attractive to a growing number of industries. For example, home users will be able to make more-complex and customizable jewelry, which could disrupt segments of the luxury goods market. Products that typically are not customized at all today, such as running shoes, could become easily customizable through advances in AM. This potential shift is illustrated in Figure 2, where running shoes move upward and cross the frontier into the space for goods that are produced through AM.

Over time, industries themselves could change and evolve as a response to the new opportunities afforded by technological growth.

Figure 2. Dimensions of Disruption



SOURCES: Expert interviews and responses from RAND workshop.

Business opportunities that do not even exist yet, such as the production of human organs, could emerge as AM further matures. Thus, products and perhaps whole industries could move to different locations in the figure even as the frontier itself advances.

Increasingly, more-complex objects are being created through AM. The environmental control system duct in an F-18 fighter jet is one example. Sixteen component parts were reduced to one: "Whereas the traditionally manufactured assembly must have its design tailored to fit the capabilities of the machine tools used to produce the part, the AM part is built precisely to fulfill its function" (Campbell et al., 2011). This trend illustrates the "complexity for free" concept that underlies the ease with which AM might be able to produce any structure, without the need for additional tooling or assembly. For complex tooled products, AM offers advantages over traditional manufacturing, which often reduces a product to many individual pieces.

Industries built around large-scale, mass-produced goods (such as T-shirts, dishes, and noncustomized bullets) are less likely to be significantly affected by AM because traditional manufacturers will likely continue to be able to produce high-quality goods at a lower cost. With modern logistics and likely future advancements in shipping and transportation (e.g., driverless vehicles), most simple, durable consumer goods can be mass-produced and easily delivered to market. While it might initially be novel to custom-print personalized toothbrushes or other everyday goods, consumer interest might soon fade, or the practice become a niche activity for hobbyists. Without significant improvements in capability, cost, or function, these products will likely continue to be produced through traditional manufacturing for the foreseeable future.

In contrast, the quick design-to-product time lines possible with AM might be better suited for small-batch, customizable wares. Such advantages can be seen in AM's ready use in rapid prototyping. This process is useful for testing and iterative design because it precludes the need to sculpt or build an object with expensive, time-intensive resources and thus reduces the cost of failure. AM is uniquely suited for these limited-run processes.

Similarly, products that are more valuable when they are customized to the particular user are good candidates for AM. Such examples include running shoes tailored to an individual's feet, as well as jewelry and other items that are valued for their personalized designs. With traditional manufacturing, it is infeasible to individually tailor designs. However, as the costs of AM decrease, the set of available customized products will expand, allowing consumers to choose between mass-produced and bespoke goods. These expanded options will have especially important implications for biomedical devices and pharmaceuticals. Already, we have seen AM used to produce prosthetics (Birrel, 2017), and this application should rapidly grow in use and scope, along with advances in genetically personalized medical treatments.

This customizable advantage also suggests a potential niche role in obsolescence management. When a product is discontinued, it can be difficult or impossible to find replacements parts. With three-dimensional scanning and AM, individual parts can be made to maintain large and expensive equipment even in the absence of the original manufacturer. For example, many firms have used AM to create replacements for discontinued parts after the original manufacturer has gone out of business. Such uses can be critical in managing legacy systems and weapons.

In traditional manufacturing processes, highly complex, customized, or inaccessible products might be extremely costly, creating incentives for reducing complexity of design and relying on well-functioning supply chains. As AM technology matures, the feasibility frontier will shift, allowing large industries and hobbyists alike to print more-complex or individually tailored products, even in remote or challenging environments.

Additive Manufacturing and Future Security Threats

Having discussed some of the conditions that will determine what industries or sectors will be most disrupted by AM, we now turn to the security implications. Based on our interviews and the expert workshop, we have identified two areas that should be of particular concern for policymakers: (1) the proliferation of kinetic and nonkinetic weapons and (2) economic dislocation. While AM

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has many potential security implications, its most-disruptive effects might be seen in these two domains.[15]

Weapons Proliferation

The development of AM will have profound security implications, shaping tactics and capabilities for state and nonstate actors alike.[16] The U.S. military is already exploring a range of applications for incorporating AM, from simplifying logistics and expediting supply chains (Sarantinos-Perrin, 2016) to rapid prototyping for solving technical problems in the field (McNally, 2017). These developments represent the approaching frontier in AM and the U.S. military's increasing investment in this technology. With the U.S. Department of Defense's new AM technology road map (Sarantinos-Perrin, 2017), AM should be expected to figure prominently in long-term military modernization and the future of conflict.[17]

Clearly, the U.S. military and related defense industries already recognize the benefits that AM offers for warfare and intelligence collection. Unfortunately, these domestic actors are not alone in this technological pursuit. China is reportedly also very interested in AM for defense purposes.[18] Foreign militaries and other actors across the developing and developed world likely have already begun to exploit this technology or will do so soon. As we will discuss in greater depth, traditional nonproliferation measures (e.g., export controls) are unlikely to contain this technology's spread as the digital world becomes embodied in physical things.

The development and spread of AM could significantly accelerate weapon proliferation and have dramatic effects on international conflict, violent extremism, and even everyday crime. At the domestic level, point-of-sale consumption will no longer be an opportunity for governmental control of risky goods, such as firearms and drones. State sovereignty is predicated on a monopoly of force and, at a minimum, the capacity to regulate arms. AM will further relax this control, giving private citizens greater access to lethal weapons and other tools of violence. States will face increasing threats to public order as everyone from protesters to members of criminal networks becomes capable of rapidly producing such weapons. At the expert workshop, one former intelligence analyst referred to this potential development as "BYOWeapon." Should it come to pass, it would further elevate the threat and risks associated with protests or other public acts of dissent.

At the state level, AM has the potential to level the playing field between competitors and attenuate asymmetric advantages that some nations (e.g., the United States) currently enjoy.[19] Since World War II, the likelihood of interstate war has declined dramatically. In part, this trend has been driven by increasing trade and a complex web of international organizations. For the international community's most-challenging problems, sanctions offer a coercive tool that stops short of interstate war. As AM proliferates, both export controls and sanctions could become far less effective. Sanctions that restrict technology and weapon transfers could be especially weakened: With access to printers, raw materials, and designs, a state could

VEOs represent some of today's greatest security threats, and they are only going to be even more dangerous with the proliferation of AM.

more easily weather the hardship of such restrictions. Perversely, AM might indirectly support the survival and rise of such states as North Korea, which would no longer suffer the same costs of withdrawing from the international community.

Furthermore, AM's value in obsolescence management will allow adversarial states to better maintain operational capabilities over time, even in the face of more-aggressive sanctions or export controls. For example, the 2015 Joint Comprehensive Plan of Action nuclear agreement between the United States and Iran specified various forms of sanctions relief for Iran. The January 2017 delivery of an Airbus A321 was particularly noteworthy: It was Iran's first new Western-made aircraft in several decades, representing a new day for a domestic airline that had become infamous for its crashes as the aging fleet struggled to fly using only "smuggled or improvised parts" (Hepher, 2017). In the future, such challenges could be overcome more easily using AM. And while AM might reduce the number of accidents, that benefit comes at the cost of weakening the effectiveness of sanctions, which represent a basic tool for managing geopolitical challenges.

But the threat of AM goes far beyond these interstate dynamics. VEOs represent some of today's greatest security threats, and they are only going to be even more dangerous with the proliferation of AM. As one interviewee stated, "Arms control will be very difficult. It worries them [policymakers] that a technology used to make jewelry could also be used to make parts for a gun or a rocket engine. It would be easy to take a machine to the middle of Russia. You can make very complex pieces without any expertise needed. It could be a big drive for making stuff that goes into missiles." As AM printers and designs proliferate, the threat and cost of nonstate violence could grow dramatically. Even in relatively stable states, AM-produced weapons and other goods will flood black markets, giving criminal networks a new revenue stream.

Tracking VEOs and their growth will become increasingly difficult. Threat assessments and other security analyses often depend on information relating to weapon sales and other material acquisitions. Tracking these flows offers law enforcement and intelligence agencies critical opportunities to assess VEO threats and map their networks. If VEOs are able to produce much of what they need through AM instead, it becomes much harder to detect or disrupt their activities until it is too late. With fewer illegal shipments to intercept or smuggling routes to track, a sudden attack might be the first sign that a VEO has developed some new, advanced capability. AM could make such attacks deadlier or more common.

This detection problem could become especially challenging as AM provides these organizations with new means to offset advantages that the United States and its partners currently enjoy. During the workshop, several security analysts raised the possibility of new countermeasures for signals intelligence (SIGINT). In the same way that conventional weapons will become harder to track and detect, so too will electronic weapons. Cheap decoys and other jamming devices might allow VEOs to disrupt SIGINT collection through nonkinetic means. Disposable, untraceable communication systems that can be printed from anywhere will make it much more difficult to counter terrorism in the future.

Finally, lone-wolf attacks could become more lethal if individuals have ready access to AM printers. Even in such countries as the United States, where semiautomatic weapons are widely accessible, AM could increase the risk of mass murder. A lone wolf will be able to draw on the vast resources available online to print his weapons of choice. AM will expand this choice set, making more-exotic weapons (e.g., bioterror delivery systems) newly accessible and increasing the potential lethality of attacks.

While public spaces will always be vulnerable, various measures have been used to decrease the severity, if not likelihood, of shootings and other attacks in private spaces (e.g., stadiums, office buildings). But AM has the potential to threaten even these relatively secure spaces. Some of the most-secure locations could be compromised if an insider gains access to an AM printer. One of our interviewees described this threat, noting that "some files for a gun were released a few years ago and had thousands of downloads. . . . It is very easy to operate a printer. You can break up a file, get parts printed in different places." Once past the body scanners and metal detectors at airports or other secure facilities, a would-be attacker only needs an on-site printer boutique and internet connection to cause mayhem.

Economic Insecurity, Trade, and Dislocations in a Multipolar World

As it becomes possible for manufacturing to become more localized, there could be a decoupling of economic prosperity and globalization. Should the growth of the AM industries correspond with parallel advancements in automation, AI, robotics, and other disruptive emergent technologies, the workforce could look dramatically different in two decades. A larger proportion of locally produced products could weaken the economic interdependencies of nations. As previously noted, one expert predicted that the growth of AM could reduce global trade by 25 percent by 2060 (Leering, 2017).

One of our more sanguine interviewees summed up his view of the future:

> It is much easier to ship bits than to ship atoms. That will affect policy. Tariffs and stuff won't be effective when all you have to do is print a file. Labor arbitrage . . . will disappear. It doesn't matter where the box that makes everything is sitting. There will be no more surcharges to ship goods across the world. Where labor is cheap, which drives manufacturing—that advantage goes away. Only the cost of energy will drive costs.

Admittedly, this view is not necessarily the consensus. During our workshop, several economists and industry experts expressed more-tempered visions of a future that would tend to look far more like the present. These more conservative predictions rest on the historical decline in transaction costs (i.e., intercontinental shipping) and ongoing erosion of labor-intensive manufacturing, both of which have already reshaped trade dynamics.

Currently, the transition to AM requires similar numbers of employees to maintain the machines, build the products, or perform finishing activities. However, AM technologies are becoming more precise and versatile. As the technology advances, fewer workers might be necessary to produce the same amount of output. A different respondent explained,

> It could be a factory in a box. With the ease of design, there is no burden of complexity. The more-skilled

> workforce is not required. With a printer, less expertise is needed. But there is still a science element to it and still technical knowhow needed. If you're only making piece parts, they must still be assembled. You still need a skilled or semiskilled workforce. You can't hit print and get a combustion engine. It'll get easier, decrease the number of parts, but you still need someone to put it together. There is the possibility of AI, robotics, AR/VR [Augmented Reality/Virtual Reality] coming together to make this happen.

Firms that use AM often require highly trained and skilled workers in contrast to large numbers of unskilled workers employed in traditional manufacturing. According to one expert, "Countries will have lower industrial production and lower participation of labor because you don't need people working on a million machines anymore." Unemployment, isolation, and alienation of middle- and low-skilled laborers could be exacerbated by AM, potentially leading to societal unrest in both developed and developing countries. The security implications of large masses of unemployed, disconnected people are substantial. Additionally, the large return to automated AM capital could further increase economic inequality, exacerbating the trend of the past 30 years and potentially leading to social unrest. It is essential that U.S. policymakers think critically about these issues and work to maximize the net benefit of continued development and deployment of AM.

Increased economic independence of developing countries could also disrupt the current world order with both positive and negative consequences (Garrett, 2014). Instead of exporting raw materials to advanced countries with extensive manufacturing capabilities, the least-developed countries could manufacture with much smaller capital investments (Berman, 2012). This could reduce the need for aid in many areas but increase economic disparities in others. The upward mobility of countries and individuals might depend on the decisions and investments of governing bodies at the onset of these movements.

As developing nations build their own AM capabilities, foreign access to raw materials could be diminished, especially for heavily dependent countries, such as China. In one interview, an expert explained that "countries will be more empowered to make their own products for their own people. Trading will be much more expensive. It may just be a new reality. Geography will dictate resources." With the advent of AM, access to rare or regionally bound raw materials, digital goods, and IP might determine the future prosperity of nations.

Mitigation Strategies and Policy Recommendations

In the previous sections, we described the disruptive potential of AM and the future security threats that this technology could unleash. This future, however, is not inevitable. Domestic and international policy choices made today have the potential to dramatically influence the future, making it incumbent that we begin to address these challenges now while the technology can still be shaped. The relative risk and cost of future threats will depend on the evolution and regulation of AM hardware (i.e., printers), raw materials, and software (i.e., IP). These three factors represent the core enablers of AM, and the potential threats of AM cannot be addressed without fully considering each of these factors.

In this final section, we explore three general strategies for addressing the security challenges of AM: threat prevention, cost mitigation, and attribution and accountability. For each strategy, we discuss policy options for influencing AM development and proliferation.

Threat Prevention

The first and best solution is preventing disruption or attack, and many different views on the feasibility of doing so were discussed in our workshop. Unfortunately, prevention is not always possible, especially when the United States is only one of many states developing this technology. AM firms are already found throughout the world, so any unilateral measures would prove highly ineffective. In the early years of nuclear technology, the United States could effectively limit its development and proliferation through unilateral measures alone. But when a technology is already in wider use or development (e.g., hypersonic weapons), then multilateral efforts (e.g., joint agreements on export controls) are necessary (Speier et al., 2017). A comprehensive regulatory approach would have to include domestic and international actors, as well as both public and private sectors. The dual-use potential of AM makes it impossible to limit the spread of this technology without also curtailing its many benefits.

Given these conditions, there are few measures that can really prevent weapon proliferation. In terms of hardware, domestic regulations could limit the purchase of printers through background checks and other constraints. At the retail level, this control would prevent (or at least slow) the spread of AM to VEOs. Such checks, however, would become ineffectual as AM printers further develop their self-duplication capabilities. These regulations would also hamper the growth of the industry and slow the advent of the huge positive benefits of AM. Further, U.S. regulations could drive the technological frontier to other countries, such as China and Russia, which could limit U.S. competitiveness in the future. Threat prevention will be more effective if focused on material controls in a highly targeted way. By limiting supplies of rare or dangerous raw materials, regulators can at least ensure that some of the most-destructive weapons (e.g., nuclear or dirty bombs) do not become readily accessible to VEOs. While it might be impossible to prevent sophisticated actors from building complicated explosive devices using AM, policymakers can at least safeguard the raw materials that amplify their destructive power.

In a similar vein, law enforcement might be able to curtail digital exchanges of lethal creations by monitoring online communities. As physical controls become less effective, police and intelligence agencies must increasingly work to secure the digital borders. A malevolent actor who has a printer and access to raw materials still needs advanced software and digital designs to create dangerous weapons. Unfortunately, the efforts of domestic law enforcement might be ineffectual on this front. After all, regardless of the ability of export controls to stem the flow of printers and

A comprehensive regulatory approach would have to include domestic and international actors, as well as both public and private sectors. The dual-use potential of AM makes it impossible to limit the spread of this technology without also curtailing its many benefits.

materials, far less can be done to limit the exchange of information. As one expert noted, "It will be very easy to design products in 3D. The distribution of the IP and the computer-aided design files will be big problems. There will be the ability to rapidly copy and slightly edit something to avoid patents laws." Even if policymakers can strengthen patent laws as a way to control the spread of ideas that they deem dangerous, online communities, black markets, and other venues for exchange will make any number of plans and designs readily accessible worldwide—an existing example of this is the prevalence of pirated movies and music (Depoorter, 2014). This avenue of communication has economic costs and makes it easier to steal designs and replicate advanced technologies—again, making export controls less effectual (McNulty, Arnas, and Campbell, 2012). Furthermore, the threat of litigation for violating patent law will not serve as a real deterrent for many actors.

Cost Mitigation

In all likelihood, these preventive measures will not stop the spread of the negative consequences of AM. There is little that regulation, export controls, treaties, and law enforcement can do to fully prevent a motivated, well-financed, and organized actor from eventually acquiring new technology. Therefore, policymakers should be particularly focused on measures for mitigating the cost of these future threats.

In terms of hardware, one possibility would be requiring online printer registration for new or more-advanced devices. Fail-safe measures could limit functionality for unregistered devices. Regular online updates could be required, without which the printer would become inoperable or lose some functionality. These measures will obviously face constant challenge (e.g., hacking) from owners and operators, who might resist such monitoring and control. Producers also might have incentives to circumvent these limitations. As users find ways to circumvent or disable these measures, their effectiveness will diminish over time.

Alternatively, law enforcement could exploit AM software to actively disrupt potential attacks or limit their destructive effects. Just as hackers might use cyberwarfare to threaten security and commerce, law enforcement and intelligence agencies could deploy similar countermeasures, compromising enemies' machines to help mitigate the costs of an attack. By infiltrating AM systems, an enemy's printer can be sabotaged, its software corrupted, and digital plans compromised. Each of these measures can help degrade the quality or lethality of an AM product. However, these infiltration measures raise a panoply of privacy and ethical issues, the full scope of which is hard to imagine today. If such aggressive measures are deemed necessary, policymakers will have to be especially careful when considering what statutory constraints are needed to limit police and intelligence agencies' use of such cybermeasures to protect the privacy rights of individuals.

As for economic dislocation, new training and education strategies should be created to prepare for the changing skill needs of future industries. In the near term, technicians and other highly specialized and trained individuals will be needed to produce and utilize the products of AM. In the longer term, sectors where human interaction is important, such as the arts, education, and service sectors, are likely to be among the least-disrupted industries and could be emphasized in future employment and vocational training programs.

Such programs should not only help provide for the basic necessities and social welfare but also address the loss of dignity for displaced workers and other populations disrupted by AM. These programs could be funded through increased taxation of automated industries, helping redistribute the gains from AM while offsetting the losses for those communities most hurt by this technology. The dangerous potential of social unrest caused by those displaced by technological advancement must be considered before and during the transition to AM and automation. Assiduous tracking of rates and patterns of employment, migration, and social discontent will enable the public and private sectors to anticipate and mitigate the effects of economic dislocation.

Attribution and Accountability

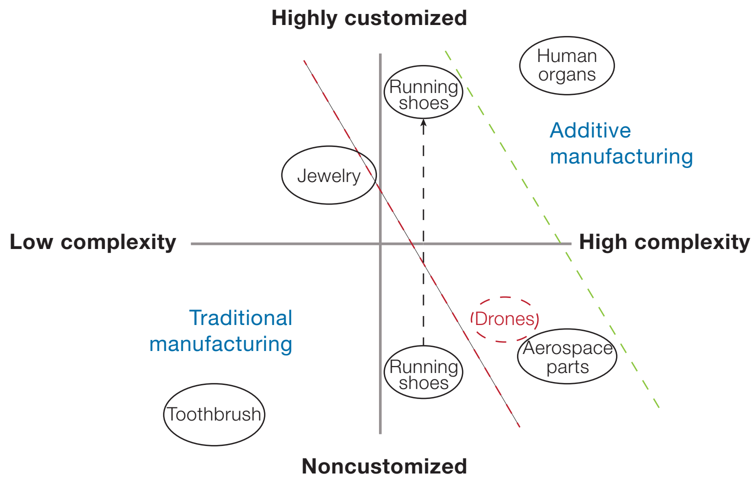
Unfortunately, not even cost mitigation will be possible in some cases. For state authorities unable to prevent or even disrupt an attack, attribution and accountability remain a last recourse. After an AM-linked attack, law enforcement will face new challenges in efforts to track down and hold the perpetrators accountable. Policymakers should consider new ways to support this process. For example, regulatory standards could require that printers encode a unique ID in their products, making attribution easier. One industry expert noted the potential for genetic-based IDs (e.g., in the raw materials), which cannot be tampered with or erased. More-restrictive controls on materials will further help attribution, particularly after attacks that use rare elements.

Many of these attribution technologies are still in the early days of development and their feasibility is still unclear. However, given the difficulties associated with prevention and cost mitigation, attribution and the threat of accountability could turn out to be the most promising areas for investment by policymakers.

Conclusion

To better capture the complicated trade-offs inherent in regulatory intervention, we return to our conceptual framework on the dimensions of disruption. Figure 3 resembles Figure 2 but includes a second technological frontier (i.e., the green line), which represents the potential effect of some proposed regulation. For example, suppose that policymakers are concerned that armed drones will become readily producible using home printers if left unregulated (i.e., the red line). With new regulations on the size and sophistication of retail printers, policymakers can shift the frontier to the right. While this regulation might solve the drone problem, it could also have unintended consequences. Innovations and development in the aerospace sector might suffer because the new AM regulations would also

Figure 3. Dimensions of Disruption and Policy Regulation



SOURCE: Expert interviews and responses from RAND workshop.

As the technology continues to develop, home users might discover work-arounds, rendering the regulation ineffectual. While this hypothetical example is wildly oversimplified, it nonetheless captures the underlying tension in regulation.

influence this sector. This regulation might even have spillover effects across other unrelated industries (e.g., shoe companies). Furthermore, this policy solution might not hold indefinitely. As the technology continues to develop, home users might discover work-arounds, rendering the regulation ineffectual. While this hypothetical example is wildly oversimplified, it nonetheless captures the underlying tension in regulation. Policymakers must negotiate the complicated choice of doing nothing with the risks and costs of intervention.

Ultimately, what is required is a heightened awareness tempered by caution. If AM continues to develop along its current trends, it could present security threats to individuals and societies. However, there are also complex trade-offs and unforeseen consequences that come with regulation. By overregulating IP, for example, policymakers might unintentionally stifle innovation. While such regulation might decrease the likelihood that VEOs develop a sophisticated weapon, it could also reduce the potential benefits of AM. And, by outlawing certain materials, policymakers might inadvertently create incentives that support an expansive and dangerous black market. Fully predicting how individuals and groups will respond to regulatory change is impossible. Awareness of potential problems, continued research, and insights from industry professionals and security experts are needed to get the balance right.

Any new technology brings potential benefits and threats. While fraught with risks, policymakers must begin to address the hard security questions that AM will bring. Decisions made today have the power to shape the opportunities and threats that will be faced in the future. While this brief paper has outlined a few potential security implications of the advent of AM, more research should be done. Now is the time to begin considering the awe-inspiring potential and possible negative consequences of this powerful new technology.

Appendix: Interview Protocol

Thank you for taking the time to speak with me today. I want to remind you that your responses to these questions will help inform U.S. policymaking on issues surrounding additive manufacturing, including research and development incentives, regulation, and strategies for shaping the emerging threat environment.

We will be reporting themes and variations in responses across interviews. We may include some direct quotes, but will not be attributing them to anyone by name or position in a way that would directly identify you. You are free to decline to answer any question or end the interview at any time.

PART I: BACKGROUND

We would like to begin with some basic background questions:

1. What is your position?
2. What does your organization do in the additive manufacturing domain?
    a. Materials production
    b. Machine production
    c. Printing services (onsite—on your premises)
    d. Printing services (off-site—printer at desired location)
    e. Finishing (sanding, painting, etc.)
    f. Design services
    g. IP/Legal/Other (please specify)
3. What types of products do your [machines/materials/other services] produce?
4. Which method(s) of additive manufacturing does your organization use?
    a. FDM (fused deposition modeling)
    b. SLA (stereolithography)
    c. DLP (digital light processing)
    d. SLS (selective laser sintering)
    e. SLM (selective laser melting)
    f. EBM (electron beam melting)
    g. LOM (laminated object manufacturing)
    h. BJ (binder jetting)
    i. MJ (material jetting/wax casting)
    j. Other (please specify)
5. How many years have you been in the Additive Manufacturing field?

PART II: INDUSTRY DYNAMICS

Now we'd like to talk about how the industry has changed over time, and ask you to speculate a bit about the future.

6. How have your printing capabilities changed and improved for your organization, in particular, and the industry in general, since you began?
7. What problematic issues have arisen for your organization, in particular, and the industry in general?
8. Where do you think your organization, and the industry in general, is headed in the next ten years? Twenty?
9. As this technology develops over the next 20 years, which industries or sectors do you think will experience the most dramatic effects?

10. Which industries or sectors will be the least affected over the next 20 years?
11. When do you think additive manufacturing printers will be used regularly by those not in the industry, such as in the home or in a community makers hub?
12. What percentage of total goods that consumers buy will include elements that were 3D printed ten years from now? Twenty? Fifty?
13. Twenty years from now, what kinds of every day goods or even specialized products and technology do you suspect will be exclusively made through additive manufacturing?
14. Can you recommend any other experts, organizations or firms that we should contact for this study?

PART III: SECURITY IMPLICATIONS

Finally, we'd like to ask you a few more speculative questions surrounding security issues and the potentially disruptive effects of Additive Manufacturing.

15. Most of our questions today have been about the industry and technology itself, but what do you think the effects will be on society, politics, and the global economy? Thinking about the next 25 or even 50 years, what does your nightmare scenario look like? What does the best possible situation look like?

We've also thought about a couple of future scenarios, which imagine a future world where additive manufacturing has developed dramatically and proliferated widely. As an industry expert, we'd like to get your opinion on the likelihood of each of these scenarios, and potential strategies that policymakers may take to mitigate these threats or even shape these futures.

Scenario 1:

The year is 2025. Transnational and homegrown terrorism is a constant threat in the West. Although based in remote locations in the developing world, violent extremist organizations and other nonstate actors have followers and cells scattered across the globe. These organizations also possess 3D printers. An emerging virtual community freely exchanges and shares the designs for weapons and explosives that are difficult to detect and of increasing lethality. Through the black market, nonstate actors can purchase metals and other polymers to easily and cheaply produce these weapons.

16. In your opinion, how likely is this scenario?
    a. Very unlikely
    b. Somewhat unlikely
    c. Neutral
    d. Somewhat likely
    e. Very likely
    f. Don't know

17. Why exactly don't you think this scenario is likely?
18. In your opinion, is there anything policymakers (national or international) could do to limit these future threats? If so, what are these policies?
19. Do you have any other thoughts on this scenario or other kinds of scenarios we should consider?

Scenario 2:

The year is 2035. Many countries that are currently considered "developing" have established a manufacturing sector through 3D printing, which requires limited human labor. Due to this trend, large portions of the population are without employment or a means to support themselves. Physical travel to these countries has become dangerous and discouraged, while trading with them for resources has become increasingly expensive.

20. In your opinion, how likely is this scenario?
    a. Very unlikely
    b. Somewhat unlikely
    c. Neutral
    d. Somewhat likely
    e. Very likely
    f. Don't know

21. Why exactly don't you think this scenario is likely?
22. In your opinion, is there anything that policymakers (national or international) could do to limit these future threats? If so, what are these policies?
23. Do you have any other thoughts on this scenario or other kinds of scenarios we should consider?

Scenario 3:

The year is 2045. International trade has dramatically diminished. With the proliferation of additive manufacturing, most states have developed their own domestic manufacturing sectors. As trade declines, migration and cross-cultural exchanges also become less common, eroding interstate relationships and the affinity among nations. Autocratic leaders now have little incentive to engage with or open up their states and economies to the international community. These emerging pariah states represent an increasing threat to international order. At the same time, competition over primary commodities (especially materials used in additive manufacturing) has increased the risk and frequency of interstate war.

24. In your opinion, how likely is this scenario?
    a. Very unlikely
    b. Somewhat unlikely
    c. Neutral
    d. Somewhat likely
    e. Very likely
    f. Don't know

25. Why exactly don't you think this scenario is likely?
26. In your opinion, is there anything policymakers (national or international) could do to limit these future threats? If so, what are these policies?
27. Do you have any other thoughts on this scenario or other kinds of scenarios we should consider?

Thank you for your time and thoughtful responses. We will be sure to follow-up with you in the future as this project develops and we have results to share.

Notes

[1] While colloquially known as three-dimensional (or 3D) printing, we will refer to this technology as AM and 3D printing interchangeably throughout this Perspective.

[2] See, for instance, Markillie (2012) and Berman (2012).

[3] While computer numerical control milling machines already allow for the home production of some weapons, they remain fairly limited in their range of lethal products. AM technology has the potential to expand this range dramatically while also reducing the cost of and access to such weapons.

[4] For more on how new technologies might slow or even reverse globalization, see Hammes (2016b).

[5] IP rights remain a point of contention for AM. Most of the current schematics used as design instructions are freely available with open-source arrangements, such as the GNU General Public License, but there is a growing number of curated, charge-based libraries. The eventual libraries of digital designs will likely be a mix of industry-based, for-profit structures and free, open-source repositories.

[6] Note that this is Leering's conservative estimate. He estimates that if investment doubles every five years, as much as two-fifths of global trade could disappear by 2040.

[7] Our semistructured interviews drew from a standard protocol and set of questions. Such a questionnaire provides structure without fully restricting the respondents' answers on more-speculative questions. For more on this method, see Rathbun (2008).

[8] Group discussions focused on five areas: law and ethics (e.g., health and IP); economic and social dislocation; trade and international order; violence and weapon proliferation; and space, communications, and surveillance.

[9] As AM infiltrates new sectors, the list of affected industries continues to grow. A sample of industries in which AM is being used includes medical and dental devices; automotive manufacturing; art, jewelry, and fashion; building construction and architecture; electronics and robotics; aerospace; food; and consumer goods. The purposes for which AM is being used or explored include (but are not limited to) obsolescence management, supply chain disruption, rapid prototyping, tooling, and research.

[10] For more discussion, see Kietzmann, Pitt, and Berthon (2015).

[11] For more on this, see Veronneau, Torrington, and Hlavka (2017).

[12] Such advances make AM particularly appealing to manufacturers hoping to serve remote locations, as well as to the National Aeronautics and Space Administration (NASA), SpaceX, and other organizations hoping to colonize off-earth locations.

[13] In addition to raw materials, the energy needed to run 3D printers represents another critical enabler.

[14] Note that it is not clear whether workshop participants included military applications with the impact of AM on government. AM is likely to be important in many military settings. The two were not separately discussed in the workshop, so it is difficult to get a sense for how those in the room viewed the potential disruptive effects of AM on the military.

[15] The workshop identified several other potential implications of AM for security. Details are available from the authors upon request.

[16] See the analysis in Hammes (2016a).

[17] See Veronneau, Torrington, and Hlavka (2017).

[18] See Fey (2017).

[19] Printable drones, for example, could reshape surveillance architecture. This change has untold social ramifications, as hobbyists can easily print their own surveillance devices.

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Acknowledgments

We would like to thank Andrew Parasiliti, Robin Meili, Steven Popper, Gregory Baumann, Doug Irving, Erin Smith, Hosay Yaqub, and Sonni Efron; without them, this project would not have been possible. We benefited immensely from the comments of our reviewers, Simon Veronneau, a management scientist at RAND, and Tim Webb, chief executive officer, Alternative Fuels Group. We would also like to acknowledge the following for their brilliant insight and helpful conversations: Edward Balkovich, Sean Barnett, Michael Bergman, Marjory S. Blumenthal, Ben Bouffard, Mel Cossette, Kathryn Edwards, Aaron Frank, Bryan Frederick, Rich Girven, Jacob Heim, Brian Jackson, Gil Mayron, Richard Neff, Sean O'Brien, Lance Pickens, Tresa Pollock, Marek Posard, James A. Regenor, Daniel Sawyer, Howard Shatz, Sally Sleeper, Robert Swartz, Danielle C. Tarraf, Jim Thomas, Geoffrey Torrington, Cortney Weinbaum, Yuna Wong, and several anonymous interviewees. All errors that remain are our own.

Security 2040

This Perspective is part of a broader effort, an initiative of RAND Ventures, to envision critical security challenges in the world of 2040, considering the effects of political, technological, social, and demographic trends that will shape those security challenges in the coming decades. The research was conducted within the RAND Center for Global Risk and Security.

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Funding for this venture was provided by gifts from RAND supporters and income from operations.

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About This Perspective

Additive manufacturing (AM)—colloquially known as three-dimensional, or 3D, printing—is an emerging technology with potential local and international security implications in the near and long terms. This Perspective—part of a series examining critical security challenges in 2040—offers a new framework for exploring the disruptive dimensions of AM technology, helping to inform which sectors and industries might be the most affected in the future. To better understand the security implications, a RAND research team briefly reviewed the existing literature, conducted interviews with stakeholders and subject-matter experts, and convened a workshop with technology and security experts. Two overarching security threats emerged: the proliferation of weapons and economic insecurity. This Perspective explores each of these security threats and offers a series of mitigation strategies and policy recommendations to help manage and regulate the negative impacts of this technology.

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PE-283-RC