3D Challenges: Ensuring Competition and Innovation in 3D Printing

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ABSTRACT

Not often does a general-purpose technology disrupt numerous markets and significantly affect social welfare. 3D printing is an exception. This technology promises to improve the quality of certain goods and to greatly increase the efficiency of their production processes. More importantly, it holds potential to reshape entire supply chains, including the design, manufacture, assembly, distribution, warehousing, and marketing of some goods, potentially even eliminating some parts of such chains. By changing the Coasean tradeoff, 3D printing also reshapes relationships between market players. This Article reviews the potential disruptive effects of 3D technology, analyzing the ways it impacts market dynamics and social welfare. It then considers the policy and institutional responses that may be required as 3D printing comes into its own, focusing on regulatory tools that foster competition and innovation. Finally, this Article identifies three main regulatory tasks that are affected by the unique characteristics of 3D printing technology.

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I. INTRODUCTION

Your best friend’s birthday is tonight, and you have not yet found her a present. You design a unique piece of jewelry using design software on your smartphone, send the file to your home printer or to the corner shop to be printed, and pick it up on your way to the party. Or imagine your car breaks down in the middle of nowhere. You need a specific kind of wrench to fix it, which you do not have in your toolbox. You simply download the relevant application and print it on-site in your car. Do these hypothetical scenarios sound like science fiction? On the contrary, 3D printing is already available, and as the technology develops further, these scenarios may become the new reality in many markets.

3D printing holds the potential to drive significant technological and organizational change across a wide number of markets. Advances in this technology challenge many assumptions about how markets operate, potentially upending all parts of traditional supply chains, including design, manufacture, assembly, distribution, and warehousing. For the provision of some goods, there will no longer be need for factories, warehouses, or distribution networks. A 3D printer, a design that fits its capabilities, and raw printing materials will suffice.1 Accordingly, this technology may significantly disrupt domestic and international production, trade, and employment patterns, creating a three-dimensional effect on firms, markets, and society.

Furthermore, by enabling more people to design products, 3D printing may change the very nature of the innovation process itself. Indeed, it constitutes an “invention of a method of inventing.” This implies that 3D printing may not only revolutionize some production processes but will also transform consumer capabilities and artistic expression. It is thus not surprising that alongside industrial users (e.g., car and aircraft manufacturers, house builders, and biomechanical firms) that are enjoying the benefits of 3D printing, 3D design marketplaces such as Pinshape and CGTrader are already selling designs for products such as footwear, jewelry, or housewares that can be fabricated by 3D home printers.

3D printing also raises a wide array of regulatory challenges. To illustrate, consider the well-known episode of the TV drama The Good Wife, in which a character is paralyzed when a gun created on a 3D printer misfires. The episode deals mainly with the moral, tort, and criminal conundrums potentially raised by 3D printing technology. Numerous scholars have focused on the intellectual property issues resulting from the ease of copying others’ product designs. This Article focuses on another piece of the regulatory puzzle, which so far has been underexplored: potential barriers to competition and innovation.

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2. See, for example, Iain M. Cockburn et al., The Impact of Artificial Intelligence on Innovation, in THE ECONOMICS OF ARTIFICIAL INTELLIGENCE 2 (Ajay K. Agrawal et al. eds., forthcoming 2019), for a discussion on how another technology is changing the innovation process.


Analyzing how to regulate competition is important not only because the advent of 3D printing will change production processes and potentially increase production efficiency but even more so because 3D printing may vastly improve dynamic efficiency—the market’s ability to generate and spread innovations in products and processes of production. By changing the ease and geographic location of the innovation process, 3D printing potentially creates a much larger laboratory for experimenting with new products. Furthermore, it enables us to construct highly intricate forms that would not be possible otherwise. Indeed, 3D printers have already been used to print nanostructures, artificial coral reefs, bioactuators that mimic octopus tentacles, human tissue and cells, and even arbitrary sequences of DNA typed out in a text file. 3D-printed homes have been fabricated in twenty-four hours, saving up to 70 percent of construction costs. Given their unmatched ability to customize with high accuracy, 3D printers also dramatically reduce the cost of custom-made medical devices, including hearing aids, dental implants, hip replacements, and artificial limbs. Experts envision that within a decade, personalized viruses dispensed from inexpensive 3D DNA fabricators may help cure cancer. 3D printing will also increasingly change not only products but services as well; your dentist can already scan your mouth and print an idiosyncratic dental crown to be fitted in your mouth on the spot.

It seems safe to say that once scientists learn to seamlessly mix inorganic and organic structures, any design that can be specified and stored as information could be materialized. Furthermore, as elaborated below, 3D printing has the potential for wide-ranging effects on social welfare, affecting, inter alia, population dispersion, equality,
and trade patterns. It can even reduce some of the ills of capitalism, such as excessive market concentration.

These effects highlight the need to ensure competition and innovation in 3D printing technology. This need is strengthened by the fact that the public might not be able to tolerate as much limitation on competition and innovation with regard to 3D printing technology, which can print kidneys and provide cancer solutions, as it does with regard to other disruptive technologies—such as online sharing of music files.

Accordingly, Part II explores the distinctive characteristics of the technology and analyzes ways in which 3D printing is changing processes, infrastructure, products, and services. Part III analyzes the potential impact of 3D printing on market dynamics and social welfare. Part IV identifies the regulatory challenges and responses for providing effective incentives for the entry, diffusion, and use of 3D printing and its complementary technologies. As this Article shows, many of the issues that 3D printing raises can be informed by the lessons learned from other disruptive technologies, such as online music sharing. At the same time, the unique characteristics of 3D printing create unique effects on incentives for innovation, the ability of markets to provide their own solutions, and the appropriate regulatory tools to be applied.

II. 3D PRINTING AND ITS TRANSFORMATIVE EFFECTS

A. What Is 3D Printing?

3D printing—more properly known as additive manufacturing—is a production process by which material is incrementally added or layered to produce a product. The printer receives its instructions from software, which determines the shape and form of each layer. 3D printing thus differs fundamentally from traditional manufacturing, in which a block of material is milled to a desired shape. As one scholar explains:

[I]ndustrial era manufacturing is typically “subtractive”: it starts with physical material—wood, metal, heated resin—and removes portions of it to create components of the eventual product, using tools, machines, or a mold. Additive

17. Id. at 44.
18. SUNDARARAJAN, supra note 1.
manufacturing is the opposite. It starts with a design, and uses a “printer” to additively construct the physical object.\(^{19}\)

Despite the connotations of its name, 3D printing is not used for copying but rather for the manufacture of a wide range of products.\(^{20}\)

How does 3D printing work? Generally, users have two options for 3D printing a desired object. They can use a premade computer-aided design (CAD) file embodying the blueprint.\(^{21}\) Such files are available for purchase or download from sites like Pirate Bay, Thingiverse, and Shapeways.\(^{22}\) Alternatively, the user can construct a blueprint of the object, using CAD or animation-modeling software.\(^{23}\) A myriad of options is then made available, from designing every aspect of the product from scratch to using an existing design file and altering it in accordance with one’s own preferences. Importantly, a preexisting image can be made into a CAD file by using a 3D scanner or by uploading photographs of an object from varying angles, allowing users to create replicas of the external contours of the original image.\(^{24}\) Once the contours are captured, the CAD file may then be altered, refined, and tailored.\(^{25}\)

As soon as a file is ready to print, a software program deconstructs the image into digital slices and sends descriptions of these to the printer.\(^{26}\) Raw material is then deposited in a series of thin layers, which the printer heats and compresses to form the object.\(^{27}\) The raw materials used may vary greatly and may include thermoplastics, modeling clay, ceramic materials, metal alloys, glass, paper, photopolymers, titanium, and even living cells and food.\(^{28}\) Advanced

\(^{19}\) Id. Of course, some industrial-era manufacturing is also additive—for example, textile manufacturing or the molding of metal. See The Textile Process, CHEMSEC TEXTILE GUIDE, http://textileguide.chemsec.org/find/get-familiar-with-your-textile-production-processes/ [https://perma.cc/XCJ8-73GD].

\(^{20}\) See, e.g., Hannah Marriott, Are We Ready to 3D Print Our Own Clothes?, GUARDIAN (July 28, 2015, 1:00 PM), http://www.theguardian.com/fashion/2015/jul/28/are-we-ready-to-print-our-own-3d-clothes [https://perma.cc/8BN3-78ZX].

\(^{21}\) Jensen-Haxel, supra note 4, at 760.

\(^{22}\) Bechtold, supra note 7, at 525.

\(^{23}\) Weller et al., supra note 16, at 46.

\(^{24}\) Bechtold, supra note 7, at 519 (“As there are no limitations in the digital representation of real-world objects, at least conceptually, nearly any shape or geometry can be reproduced with a 3D printer.”); Viola Elam, CAD Files and European Design Law, 7 J. INTELL. PROF. INFO. TECH. & E-COM. L. 146, 146–47 (2016).

\(^{25}\) Bechtold, supra note 7, at 519.


\(^{27}\) Id.

\(^{28}\) Bechtold, supra note 7, at 520.
printers can create products from several different materials used in combination.\textsuperscript{29} Materials come in the form of powders, filaments, liquids, or sheets.\textsuperscript{30}

3D printing has three key properties.\textsuperscript{31} First, printers can produce complete yet intricate products. Second, making entirely different objects does not necessarily require different production facilities.\textsuperscript{32} Rather, in many cases, idiosyncratic designs can be created on the same printer without significant extra cost.\textsuperscript{33} In economic terms, 3D printers reduce asset specificity, since the printer can be used across multiple situations and purposes.\textsuperscript{34} Third, 3D printers can translate a digital design into a physical object, tempered only by the inherent limits of the printer (e.g., the materials the device can use and the resolution with which it can deposit that material). The combination of powerful computer simulations that emulate reality, 3D scanners that can scan physical objects, and the ability of 3D printers to accurately translate and materialize intricate shapes significantly expands the universe of potential products.\textsuperscript{35} To these, a fourth trait of 3D printers should be added: 3D printers increase the user’s capacity for self-design and self-production.\textsuperscript{36}

Three main models for the use of 3D printers can be identified, differing in the locus of the printing activity. The first model, manufacturer printing, occurs in the manufacturer’s facilities. This is the case, for example, when Boeing prints its wings in its own production facilities.\textsuperscript{37} The printer can be used to print highly customized parts or, in some cases, may enable more efficient mass production.\textsuperscript{38}

\begin{itemize}
  \item[29.] Jensen-Haxel, supra note 4, at 761.
  \item[30.] Id.; Syed A.M. Tofail et al., \textit{Additive Manufacturing: Scientific and Technological Challenges, Market Uptake and Opportunities}, 21 MATERIALS TODAY 22, 28 (2018).
  \item[31.] Jensen-Haxel, supra note 4, at 760.
  \item[32.] Id.
  \item[33.] Id.
  \item[34.] See Will Kenton, \textit{Asset Specificity}, INVESTOPEDIA (Feb. 10, 2018), https://www.investopedia.com/terms/a/asset-specificity.asp[https://perma.cc/Q8JE-4JJZ]. Of course, some traditional manufacturing facilities may also not be asset-specific. Metal-object production serves as an example, since the heating equipment and the funnel for pouring the molten metal into a mold are not asset specific. Yet the mold is asset-specific and might be costly and difficult to replace relative to a design file. See YVONNE DEAN, MATERIALS TECHNOLOGY 154 (Routledge 2014) (1996).
  \item[35.] Jensen-Haxel, supra note 4, at 760–61.
  \item[36.] Id. at 763.
  \item[38.] Id.
\end{itemize}
The second type, home printing, is performed by the end user in a location chosen by him, such as his home, his office, or his car. In the episode of The Good Wife noted above, the gun was printed at the shooter’s home.\textsuperscript{39} The fact that 3D printing does not need molds, but rather only requires software applications, a printer, and raw materials, enables flexibility in the location for manufacturing at least some types of goods.\textsuperscript{40}

The last, local printing, is a hybrid model. It applies when the user of the 3D printer chooses the file to be printed and the printing is performed in a centralized location. The printer might be situated relatively close to the consumer, enabling him to collect the printed product. For instance, large retailers such as Staples have on-site 3D printers for customers to print their designs.\textsuperscript{41} Alternatively, products can be printed and then shipped to users.\textsuperscript{42}

The home and local printing models separate the design and manufacturing segments; firms sell product designs and delegate the actual production to consumers, potentially also enabling consumers to customize the chosen design.\textsuperscript{43} The printers used in the home printing model are generally much less sophisticated and much less expensive than in the other two models.\textsuperscript{44} As elaborated below, the three models have different implications for supply chain management.

\textbf{B. The Expected Growth of 3D Printing}

Though invented in the early 1980s, 3D technology has gained momentum only in the past few years.\textsuperscript{45} More consumers have been exposed to the technology, and new products have been successfully

\textsuperscript{39} The Good Wife, supra note 6.
\textsuperscript{41} Jensen-Haxel, supra note 4, at 759.
\textsuperscript{42} Kelsey B. Wilbanks, \textit{The Challenges of 3D Printing to the Repair-Reconstruction Doctrine in Patent Law}, 20 GEO. MASON L. REV. 1147, 1154 (2013) (“Online services like Shapeways, Sculpteo, and i.materialize print consumer CAD design submissions and ship the objects to consumers.”).
\textsuperscript{44} Bechtold, supra note 7, at 526.
introduced. Manufacturer printing is already used in some manufacturing processes, and the use of local and home printers is rising, with sales of home printers having crossed the seven billion line. Indeed, a survey conducted by the Harvard Business Review found that 30 percent of the world’s top three hundred global brands were using or evaluating 3D printing. Yet the technology is far from reaching its potential because, despite their many benefits, 3D printers have several limitations that prevent them from becoming more prevalent.

One major obstacle relates to the constraints on raw printing materials. For the printed layers to be combined into a whole, the materials must physically bind together layer after layer. Only certain materials have the necessary physical properties. Moreover, the costs of materials, as well as the printers themselves, are still quite high. Yet as the industry progresses, new materials and new layering technologies are being developed.

Home printing creates additional challenges relating to the size and functionality of 3D printers. Small- and medium-sized printers may take a long time to print even small objects. On a home printer, printing a four-centimeter model may take about fifty minutes. Printers—and the materials they rely on—also take up space. Thus, for most home purposes, relying on brick-and-mortar or online shopping may be the most appealing option. Some consumers may also enjoy traditional shopping and be reluctant to give it up.

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46. These include, for example, organic hearts and kidneys, as well as dental crowns noted above. Burt, supra note 12.
49. Id. at 46.
50. Id. at 46.
52. Weller et al., supra note 16, at 44.
54. Id.
any other digital device, the risk of viruses and other cyber harms arises.56

As 3D printing and its complementary technologies develop further, it is expected that some of these costs and limitations will be reduced. For example, virtual reality might be used in conjunction with 3D printing to create a virtual shopping experience—perhaps even a joint virtual shopping experience with friends.57 Users will virtually explore the options that can be printed, choose their preferred design, and send an order to the printer. With respect to cost limitations, market actors are already investing in ways to reduce the costs of printing materials and printers.58 Indeed, a growing number of products are produced at lower cost and much faster than via traditional manufacturing.59

According to Arun Sundararajan, in the future, households will regularly own a 3D printer that can print numerous types of small physical products, and local printer shops will be commonplace, providing the opportunity to print bigger, more complex goods.60 This prediction is not without support. Many industry analysts predict that 3D printing will eventually become the standard production method.61 Stefan Bechtold notes, “[F]orecasts on the potential impact of 3D printing technologies in the future range from cautiously optimistic to enthusiastic. . . . They will play an increasingly important role both in rapid prototyping and in the production of product components and finished products.”62

Of course, not all manufacturing will change. For some products, traditional manufacturing will retain a comparative advantage in terms of economies of scale and scope, as well as in quality and speed.63 Nonetheless, 3D printing is likely to affect numerous markets.

56. Jensen-Haxel, supra note 4, at 739.
57. See, e.g., The 360 Mall, https://www.the360mall.com/ [https://perma.cc/TJ97-ZBXN].
60. SUNDARARAJAN, supra note 1.
62. Bechtold, supra note 7, at 522.
63. For the advantages and limitations of 3D printing see, for example, Weller et al., supra note 16, at 48.
C. 3D Printing’s Disruptive Effects on the Supply Chain

The emergent 3D technology can completely transform supply chains as well as internal firm structures in some industries. To see how, it is useful to analyze its effects on all parts of the supply chain.

Traditional supply chains generally consist of the following separate steps: product design (including prototyping), procurement of necessary raw materials, manufacturing, assembly, warehousing, marketing, distribution, and spare parts management. This Article explores the effects of 3D printing on each part of the supply chain.

Figure 1. Traditional Supply Chain

3D printing affects product design in several ways. First, it allows for rapid prototyping, reducing the product development process cycle time. No longer must firms create and test new physical molds for new products; now they can change the product graphically and review the printed outcome almost immediately. Shorter and less expensive product development processes can make firms more responsive to market changes.

More importantly, 3D printing may change the optimal design of products. It enables objects comprising intricate parts to be produced as a whole, thereby overcoming some assembly limitations and potentially positively affecting other quality parameters, such as safety. This can significantly improve product design, as illustrated in

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64. Waller & Fawcett, supra note 5.
65. See Bechtold, supra note 7, at 522; David Braue, Let’s Get Physical: How 3D Printing Works, APC (Nov. 29, 2011, 6:00 AM), http://apcmag.com/lets-get-physical-how-3d-printing-works.htm [https://perma.cc/3NBS-XQL4] (3D “has become a favoured way of prototyping new products without [costly manufacturing lines]”).
66. Waller & Fawcett, supra note 5.
68. See, e.g., Weller et al., supra note 16, at 45–46.
the aircraft industry. Airplane engines are among the most delicate and intricate of manufactured goods, involving many small parts that interconnect in sophisticated ways. Until recently, many parts were produced by different manufacturers and carefully assembled. Assembly limitations, such as the need to assemble the engine from its core outwards, influenced how engines were structured. All this has changed. 3D technographic advances, coupled with 3D printing, have enabled a new and greatly improved mode of manufacture for some engine parts. The sequence of assembly inside such parts is no longer important; the printer can print internal and external parts of the engine at the same time, even if they are made of different materials. The result is better engines.

3D printing’s ability to make mass customization a reality further affects product design. The ease of creating designs for printing implies that many more products will be designed by more designers or even users-turned-designers. Consider a lampshade, which has few essential features (namely, connections for a cord and a lightbulb, as well as fireproof materials). With relatively simple software, each user can design her own lampshade. Indeed, several years ago the Museum of Arts and Design in New York exhibited software that enabled users to design lampshades based on their movements in a defined space; the designed product could then be printed on a 3D printer. Such software enables end users to create...
one-of-a-kind designs and determine the product’s desired material, form, and surface finish.\textsuperscript{80} This, in turn, exponentially increases the consumer’s options, opening the door to all sorts of innovations, designed by others or even by oneself.\textsuperscript{81} For consumers, this could mean not only products that better reflect their preferences but also improved well-being through self-empowerment or artistic expression.\textsuperscript{82} Accordingly, 3D printing may enable the design of products that the world wants but does not know yet, because those products do not fit neatly into the mass economics of the old model.\textsuperscript{83} Furthermore, the exponential increase in designers, due in part to consumers-turned-designers, may act as a laboratory for product improvements.\textsuperscript{84} Indeed, companies may attempt to facilitate innovative user communities, creating feedback loops between the companies and their consumers.\textsuperscript{85}

3D printing can also completely transform manufacturing. Not only are goods produced in a new way (i.e., by printing layers rather than molding) but the same printer may be able to manufacture all kinds of different products.\textsuperscript{86} As Francisco Beneke observes, “[M]anufacturing across industries will be performed by machinery that is not market- or firm-specific.”\textsuperscript{87} This implies that sunk costs in manufacturing facilities may be significantly reduced.\textsuperscript{88} In addition, 3D printing may lower the costs of producing limited-series products.\textsuperscript{89} It may also reduce the need for mass production, at least for some goods. Furthermore, 3D printing may reduce the amount of material used in the production process.\textsuperscript{90} In some cases, the amount of material required is 95 percent less.\textsuperscript{91} By reducing the total number of

\begin{thebibliography}{99}

\bibitem{80} Sethuraman et al., \textit{supra} note 43.
\bibitem{81} Pamela Samuelson, \textit{Freedom to Tinker}, 17 THEORETICAL INQUIRIES L. 563, 574 (2016).
\bibitem{82} Some users might experience negative emotions, such as feeling inept at designing.
\bibitem{83} \textsc{Chris Anderson}, \textsc{Makers: The New Industrial Revolution} 221–22 (2012).
\bibitem{84} Bechtold, \textit{supra} note 7, at 532.
\bibitem{85} \textit{Id.}
\bibitem{86} See discussion \textit{supra} Section II.A.
\bibitem{88} See discussion of asset specificity \textit{infra} Section III.A.
\bibitem{89} Bechtold, \textit{supra} note 7, at 520.
\bibitem{90} \textit{Advanced Manufacturing: Adding and Taking Away}, \textsc{Economist} (Dec. 31, 2013), https://www.economist.com/babbage/2013/12/31/adding-and-taking-away [https://perma.cc/2WMJ-5BH7].
\bibitem{91} \textit{Id.}
\end{thebibliography}
components that must be assembled to create a finished product and altering the sequence of assembly, it may reduce assembly costs and eliminate some assembly limitations.

Distribution and marketing are also upended by the 3D printing revolution. For products that can be customized on a mass scale, mass distribution and marketing will no longer be needed. In addition, transport of finished goods will diminish, while transport of raw printing materials will increase.

Finally, 3D printing also affects inventory management and warehousing. Managing an inventory, whether of new goods or spare parts, is often complicated and costly. This is a natural outgrowth of traditional constraints on the manufacture and distribution of goods. Take, for example, the management of time-sensitive spare parts. Because demand for replacement parts can be difficult to predict, spare parts for some products must be held in multiple locations or transported over long distances by expensive expedited shipping methods. With 3D printing, the user could print the part as needed, when needed, on location. Accordingly, 3D printing can potentially alter all parts of the supply chain across numerous industries.

III. EFFECTS ON COMPETITION AND WELFARE

3D printing’s disruption of the supply chain affects market dynamics. Such effects must be recognized in order to determine whether and what kind of regulatory oversight might be needed. Accordingly, this Part identifies and analyzes the broad, multifaceted effects of 3D printing on competition and social welfare.


96. Id.

97. LIPSON & KURMAN, supra note 61, at 22

98. Id. at 205.

99. Waller & Fawcett, supra note 5.

100. SUNDARARAJAN, supra note 1, at 72.
A. Effects on Competition

3D printing technology changes market dynamics, thereby potentially affecting all parameters of competition. First, consider how manufacturer printing affects competition. As elaborated above, the major changes brought about by such printing are in the design, manufacture, and assembly segments of the supply chain.\(^{101}\) Assemble-by-design technology reduces the need for the separate creation of components and assembly of the final product, thereby potentially reducing costs and increasing quality.\(^{102}\) These changes also make some existing elements of firms’ internal organizations redundant. In addition, given that 3D printing makes prototyping and customization much faster and easier, firms employing 3D printing may be more responsive to idiosyncratic demands or to demand changes.\(^{103}\) This, in turn, may affect their competitiveness, as well as product cycles.

3D printing may also reshape external vertical relationships\(^{104}\) by changing the Coasean tradeoff,\(^{105}\) according to which firms internalize production processes so long as the costs of internal management are lower than the transaction costs of market relationships. On one hand, it may make the external procurement of some inputs or services obsolete,\(^{106}\) thereby eliminating some vertical relationships. On the other hand, it may incentivize firms to contract out the manufacture of some inputs. Whether a firm decides to outsource component production depends on many factors, including the firm’s comparative advantages in 3D printing (such as the ownership of intellectual property rights in a certain type of printer or ink, or experience with such printing), transportation costs, and the ability to control the quality of products printed by other firms (strengthened by the fact that internal components might now be less visible).

The unique characteristics of 3D printing technology noted above also affect this tradeoff. First, 3D printers are developing quickly,

\(^{101}\) Supra Section II.C.
\(^{102}\) Supra Section II.A.
\(^{103}\) Weller et al., supra note 16, at 47.
\(^{105}\) See generally Ronald Coase, The Nature of the Firm, 4 ECONOMICA 386 (1937).
\(^{106}\) See Aston, supra note 37.
potentially making early 3D printing technologies rapidly obsolete; this increases the risk of sunk costs in what might quickly become an obsolete printer and increases the incentive to contract out. Second, 3D printers have low asset specificity,\textsuperscript{107} which increases their redeployability; this could encourage or discourage outsourcing. Outsourcing could increase if other firms can use the printer more efficiently by printing a wider array of different products. The reduction in asset specificity could also allow more firms to enter the market relatively easily, increase competition for the printing of inputs, and thereby reduce the cost of outsourcing. Lastly, because 3D printers give both owners and users of printers more flexibility, they reduce imbalances in bargaining power; this reduces the need for a restrictive contractual relationship, lowers transaction costs, and encourages outsourcing.\textsuperscript{108} To illustrate, assume that an external supplier must invest in a production facility that is not deployable, such as the unique metal stamping molds used to manufacture car bodies.\textsuperscript{109} If this supplier’s sunk costs are high, it will not invest in the facility without assurances that it will be able to cover its costs, perhaps via a long-term commitment from the buyer to buy exclusively from it at a certain price level.\textsuperscript{110} 3D printing reduces the need for such commitments. Accordingly, 3D printing’s characteristics can encourage external procurement by reducing the cost of contractual relationships between market players. 3D printing thus affects vertical market relationships.

Local and home printing also influence market dynamics. Where mass production is not preferable, at least by most users, home printing will eliminate whole parts of the supply chain, creating a “lean” supply chain comprising design, marketing, materials, and production.\textsuperscript{111} Furthermore, the latter two parts of the chain will be performed by the end consumer, either at home or by using a local printer. The first part of the chain, design, can be performed by the user of the printer or by the market. Where the user does not engage in self-design, creating designs and marketing them to consumers will become the most

\textsuperscript{107}. \textit{See supra} Section II.B.

\textsuperscript{108}. For the seminal work on the effect of contractual difficulties on internal vertical integration, see Benjamin Klein et al., \textit{Vertical Integration, Appropriable Rents, and the Competitive Contracting Process}, 21 J. L. & ECON. 297 (1978).

\textsuperscript{109}. \textit{Id.}


\textsuperscript{111}. This may be the case, for example, when most users would like to design their own products or when they prefer custom-made products.
valuable parts of the supply chain. Where small entrepreneurs use such printers, there is one more link—distribution—at the end of the supply chain.

**Figure 2. The Lean Supply Chain**

![Lean Supply Chain Diagram]

In this setting, home printing will significantly reduce entry barriers, increasing competition. Entry barriers will be lowered by a combination of factors. First, home printing will make some parts of the production chain, as well as the comparative advantages based on them, such as the location of manufacture or the size of the retail store, irrelevant. Second, home printing can enable microinventors-turned-entrepreneurs to start manufacturing—and even profiting—at a small scale and gradually grow larger without significant sunk costs and with increased flexibility to changes in market demand. Third, in principle, 3D printers can be rented to or shared by many users, lowering entry barriers. At the same time, home printing could also increase some entry barriers. The abundance of designs might increase search costs of consumers, though this problem may be partially mitigated by intermediate platforms. Shorter product cycles, arising from the fact that actual production of some goods might be shorter, might increase the risk of sunk costs; at the same time, sunk costs in some product designs are likely to be very low. Furthermore, customization might lead to the disappearance of a competitive benchmark price, making it harder for potential entrants to determine what price they should and can charge, in order to assess whether their entry would be profitable. Taking all of the above factors into account, this Article predicts that the cumulative effect of home printing will likely be a reduction in entry barriers for many product markets, but not for all.

The lowering of entry barriers will increase potential competition among 3D product designers and also between such designers and mass production manufacturers. Indeed, even if many

112. See discussion supra Section II.A.
113. SUNDARARAJAN, supra note 1, at 58.
115. Supra, this paragraph.
116. Id.
products in a given market continue to be mass-produced, 3D printing may still increase competitive pressures on traditional manufacturers. To illustrate, one can buy a smartphone case cheaply online but at the cost of reduced design choice and the time for delivery. Accordingly, the cost of self-printing may serve as the upper bound in the market. Some markets may therefore be much less centralized, reducing concerns regarding unduly concentrated market power.

3D printing technology may therefore affect all parameters of competition. It may improve product quality and increase dynamic efficiency by, inter alia, enlarging the number of those engaged in design activity, increasing design choices, and enabling easier customization, thereby allowing suppliers to more easily meet the unique preferences and needs of different consumers. It may reduce the price of some products due to potential reductions in the cost of certain steps in the supply chain, in the quantities of raw materials needed, and in market concentration. The availability of products is also positively affected by changing the locus of manufacture and by increasing responsiveness to changes in demand patterns. For goods that are easily replaceable, factors such as fashion trends or changes in personal taste may result in a quicker turnover of products. The ease of production may also affect products’ properties, potentially reducing the need for long-term durability.

B. Effects on Social Welfare

3D printing technology will also bring about changes that have important socioeconomic implications that go far beyond production and dynamic efficiency. Indeed, 3D printing can potentially impact growth and productivity, as well as domestic and international trade and transport patterns. When assembly costs are high, firms may choose to locate their assembly lines where such costs are low. By reducing the need for manual assembly, 3D printing brings manufacturing closer to consumers, thereby changing trade patterns. 3D printing may also affect employment patterns, as it will reduce the need for assembly workers and operators of many different types of manufacturing facilities, while it will increase demand for designers.

117. For the effects on production and dynamic efficiency, see supra Section III.A.
119. Id.
120. Id.
By reducing distribution costs, home and local printers may enable consumers to live more comfortably in more remote areas. Assume that a machine breaks down in a remote area. To fix it, a unique part is needed. Traditionally, it may take a long time to deliver the broken part, and shipping costs might be high. Alternatively, buying the part from a local supplier might be costly due to the costs of holding a large inventory of spare parts and due to the supplier’s unequal bargaining power resulting from its unique ability to provide the part on demand. 3D printing creates a third option: downloading a design file and printing the necessary part immediately. This, in turn, completely upends cost and quality of life considerations in remote areas, so long as the printing materials are available on-site. Accordingly, 3D printing might affect population distributions, settlement patterns, housing costs, business models, and even equality of opportunity.

By reducing the need for distribution and the amount of raw materials needed, 3D printing technology can also promote sustainability. 3D printing could also reduce consumption. While the ease of printing may increase consumption, the ability to print as needed lessens the need for inventory. Furthermore, the reduction in scarcity might reduce incentives for users to own certain products in situations in which unique ownership may factor into the user’s demand function.

Finally, this method of production could serve as a partial solution to suboptimal concentrations of market power, in at least some industries. By reducing the need for large capital investments in prototyping and manufacturing facilities, assembly lines, distribution, and retail, 3D printing allows more investors to enter the market, changing not only the locus of market power but also the ability to enjoy market power in the first place.\footnote{Bechtold, supra note 7, at 522. Market power is the ability of a market player to raise his price above cost and yet not lose a large enough number of consumers to make the increase in price unprofitable. See Will Kenton, \textit{Market Power}, INVESTOPEDIA (May 10, 2019), https://www.investopedia.com/terms/m/market-power.asp [https://perma.cc/2EP5-4WGG].} 3D printing may thus counter—or at least reduce—some of the causes of market power, including economies of scale and economies of scope, in some industries.

\section*{C. Effects on Incentives to Innovate}

An important issue for competition and welfare involves the effects of 3D printing technology on incentives to innovate.\footnote{A vast literature exists on this issue. See, e.g., sources cited supra, note 7.} Even if better quality products can theoretically be printed using the
technology, the law must ensure that those who might invest in designing the better quality products—including better 3D printers—actually do so.

Two opposing effects can be identified. On one hand, by lowering entry barriers into product design and production, 3D printing potentially increases dynamic efficiency and therefore encourages innovation. On the other hand, by making it easier to accurately and rapidly copy designs, 3D printing can reduce economic incentives to innovate. Indeed, one can simply download a design file and print it. Alternatively, the physical image of a product could be captured and turned into a design file, thereby extending the copying concern to any object that can be accurately translated into a CAD file and materialized by a 3D printer. In addition, home printing makes it more difficult to detect infringements of intellectual property or to bring infringers to court, given the potential for infringements by many small users printing in private locations. The combination of these factors could reduce the incentives of designers to innovate. Unless the industry finds a new equilibrium that creates sufficient incentives for innovation—such as those found in the music or media industries, which have largely reinvented themselves based on different revenue sources—dynamic efficiency in at least some products could be significantly reduced.

The challenge created by 3D printing is much greater than in other industries—such as music or media—that have also suffered from increased copying of content. This is because, in both music and media, the innovator can at least partially control the first viewing of the protected content. The New York Times, for example, can lock its

123. See discussion supra Part II.
124. Brean, supra note 7 at 774, 781. Unlike the copying of digital files of music or other content, which is almost costless, in the case of 3D printing, creating the copied product involves the use of physical (and potentially costly) materials. John M. Newman, The Myth of Free, 86 GEO. WASH. L. REV. 513, 569–70 (2018). While this fact might reduce incentives to copy some objects, it will generally not sufficiently reduce copying incentives. Brean, supra note 7, at 775–80.
125. Bechtold, supra note 7, at 528. Private or noncommercial use does not generally exempt users from the application of intellectual property laws. Id.
126. Id. As Bechtold suggests, such enforcement difficulties may lead to questions regarding intermediary liability by design platforms. Id. at 529. Manufacturers of 3D printers might also be seen by some as facilitators of infringement. Id. at 530. This, in turn, increases uncertainty around investment in creating better printers. Id. at 525. Indeed, the better the printer, the greater the threat of infringement. Id. at 528.
128. See, e.g., Lemley, supra note 127; Oberholzer-Gee & Strumpf, supra note 127 at 2, 38.
content so that only registered subscribers can view it. Also, since copying and use in both industries is largely based on digital files, content can potentially be watermarked or tracked by low-cost digital means.\textsuperscript{129} Furthermore, the digital nature of such content has made possible the adoption of a revenue model based on paid content or commercial ads.\textsuperscript{130} These characteristics do not apply to 3D printing when the act of copying is based on the replication of physical products by converting their images into design files. Accordingly, copying may not require the viewing of the original design file of the copied product.\textsuperscript{131}

At the same time, some factors mitigate the concerns regarding innovation motivations affected by 3D printing. Not every printer is able to use every material or combination of materials in order to copy the original, and some materials cannot be used in any 3D printer.\textsuperscript{132} This also implies that it might be more difficult to hide the copying of goods that can only be printed on a certain type of a 3D printer—one that is likely to be highly costly and thus used only by a few large market players.

Also, a 3D scanner can only delineate the external contours of an object.\textsuperscript{133} Where internal composition or structure is important and cannot be easily copied by other means, the risks of reverse engineering are reduced. Design competition might, therefore, concentrate on products that cannot be easily copied. These two obstacles might diminish as 3D printing and its complementary technologies develop further.

Yet another quality of 3D printing, which is not likely to change, partly mitigates the reduction in incentives to innovate. 3D printing reduces the investment costs necessary to design some products and enter the market, enabling designers to more easily break even, at least with regard to some products. This, in turn, reduces the concern that firms will not be able to recover their costs because of the ease of free riding.

\textsuperscript{129} Anastasios Tefas et al., \textit{Watermarking Techniques for Image Authentication and Copyright Protection}, in \textit{HANDBOOK OF IMAGE AND VIDEO PROCESSING} 1083 (Al Bovik ed., 2nd ed. 2005).


\textsuperscript{131} See discussion supra Section II.A.


\textsuperscript{133} CREAFORM, INC., \textit{AN INTRODUCTION TO 3D SCANNING} 20 (2015) (ebook).
To summarize, 3D printing may disrupt current market dynamics and competition in numerous ways. Embracing the chaos can bring about significant economic benefits, both to consumers and to society at large. Yet to achieve this goal, obstacles to competition and innovation must be overcome.

IV. REGULATION OF COMPETITION AND INNOVATION

The potential disruptive effects of 3D printing across numerous markets require lawmakers to determine whether the regulatory toolbox is equipped to ensure that the anticipated changes encourage competition and promote welfare. The policy challenge is multidimensional since it involves providing appropriate incentives for the development and use of the technology across a wide number of distinct markets. This Article focuses on one subset of issues: obstacles to the efficient functioning of markets related to 3D printing. This analysis is based on the assumption that 3D printing is beneficial overall and that relatively efficient solutions can be found for other issues, such as product liability and the increased ability to create potentially harmful products (like firearms).

This analysis identifies three main regulatory challenges: incentivizing investment and innovation in 3D printers and complementary technologies, removing artificial entry barriers designed to prevent the ability of 3D printers to reach product markets, and preventing the monopolization of market power in 3D printing markets. While many of the regulatory issues explored are not unique to 3D printing, analyzing them in this context raises interesting and idiosyncratic issues. The first challenge deals with regulation for innovation, designed to stimulate innovation, while the last involves regulation of innovation, which takes innovation as given and seeks to maximize its benefits and minimize its risks. The second challenge is a combination of both. Mapping and recognizing such challenges may reduce both market and regulatory failure.

A. Incentivizing Investment and Innovation in 3D Printers

To ensure that the public enjoys the significant benefits generated by 3D printing technology, lawmakers must reduce artificial barriers to investment in the development of 3D printing. At first glance, the numerous uses of 3D printers and their potentially

134. Cockburn et al., supra note 2, at 8.
wide-ranging positive effects on welfare should create strong incentives for private firms to develop 3D printing technology. Yet precisely these traits could lead to underinvestment in the technology. This investment challenge has several facets.

The simplest one focuses on users and is especially applicable to home printers. Due to information asymmetries—partly due to the novelty of the production process—or bounded foreseeability, users who contemplate buying a 3D printer may encounter difficulties in quantifying all of its potential benefits. This may influence their willingness to invest in a 3D printer, especially if the up-front investment is high. This problem, which affects other technologies as well, can be at least be partly overcome through the pricing of complementary goods, like ink, which indirectly signify the actual costs of using the printer. Regulators need to be aware of these considerations when analyzing the effects on welfare of tying, a point this Article returns to below.

More significant underinvestment concerns arise from the fact that private consumption decisions may not reflect the wider positive externalities created by the technology, such as potentially increasing geographic population dispersion or rebalancing international trade levels. Indeed, this is a well-known challenge in innovation economics; investment may be suboptimal when private and social returns diverge and private decisions do not take into account wider social returns.

137. Such two-staged pricing is, in fact, common in markets for traditional printers. For such conduct in the 3D printer context see DSM Desotech, Inc. v. 3D Sys. Corp., 749 F.3d 1332, 1346–47 (Fed. Cir. 2014).
138. See supra Section III.C. Tying is an arrangement in which a supplier bundles the sale of two or more products. Will Kenton, Tying, INVESTOPEDIA (Apr. 14, 2018), https://www.investopedia.com/terms/t/tying.asp [https://perma.cc/XX8B-NHKL].
139. On the sharing economy see, for example, Shelly Kreiczer-Levy, Share, Own, Access, 36 YALE L. & POLY REV. 155, 157–58 (2018).
The latter could result, *inter alia*, from information asymmetries or collective action problems.\textsuperscript{141}

The fact that 3D printing is a general-purpose technology may further exacerbate investment challenges, as this means that those investing in its development may not be able to take advantage of all its potential benefits.\textsuperscript{142} General-purpose technologies are technologies that significantly affect multiple sectors, like microprocessors in information technology markets\textsuperscript{143} or deep learning in sectors that rely on data analysis.\textsuperscript{144} The development of a general-purpose technology gives rise to both vertical and horizontal positive externalities in the innovation process.\textsuperscript{145} When such externalities cannot be fully captured by those investing in developing the technology, private and social incentives could be misaligned.\textsuperscript{146} Where positive externalities exist “between the general-purpose technology and each of the application sectors, lack of incentives in one sector can . . . result in a system-wide reduction in innovative investment itself.”\textsuperscript{147} This concern may be deepened when some or all of the fruits of success can only be captured by successive innovators.\textsuperscript{148} Lack of incentives for early-stage innovation might inhibit the invention of the tools required for subsequent innovation. At the same time, incentivizing such innovation with strong property rights without adequate contracting opportunities may result in “hold-ups” for later-stage innovators.\textsuperscript{149}

Consider the following example. Assume that developing a new 3D printing technology, the ability to use multiple types of ink in one product, requires costly experimentation. Further assume that these experiments are best performed in a specific sector (such as aircraft engines) but that they have positive applications in many other sectors.


\textsuperscript{142} Cockburn et al., *supra* note 2, at 5, 8.

\textsuperscript{143} *Id.* at 5–6; Timothy F. Bresnahan & Shane Greenstein, *Technological Competition and the Structure of the Computer Industry*, 47 J. INDUS. ECON. 1, 16 (1999).

\textsuperscript{144} Cockburn et al., *supra* note 2, at 3, 22.

\textsuperscript{145} Bresnahan & Trajtenberg, *supra* note 140, at 2. Vertical positive externalities occur when an investment in one part of the supply chain also creates benefits in another part of the chain without a need for investment by the latter. *Id.* at 2, 18. Horizontal positive externalities occur when the beneficiary is a competitor. *Id.* at 2, 19.

\textsuperscript{146} *Id.* at 2–3.

\textsuperscript{147} Cockburn et al., *supra* note 2, at 5.


Investment will be commensurate with the technology’s overall benefits only if consumers in the specific sector have sufficiently high private incentives to experiment, or if the developers can capture a sufficient amount of intersectoral or intertemporal positive externalities to make their investment worthwhile. Furthermore, the public will not reap some of the wider socioeconomic benefits of 3D technology since those benefits will not be economically captured by the developers. Overcoming such obstacles may increase both private and social welfare: investment should lead to a reinforcing cycle of innovation between a myriad of application sectors and generate economy-wide transformations.¹⁵⁰

Therefore, regulation is needed to align private and social investment incentives. Solutions may involve, for example, protecting intellectual property rights in 3D printing technology in a manner sensitive to intertemporal and intersectoral externalities,¹⁵¹ subsidizing the development of the technology directly or indirectly (e.g., through academic institutions)¹⁵² or promoting the spread of information about 3D printing’s traits (e.g., its abilities and comparative advantages). In doing so, the government acts as an enabler and promoter of an innovation that carries significant potential to increase social welfare.¹⁵³ While such regulatory intervention goes beyond measures taken with regard to many other technologies, the potential significant effects of 3D printing on welfare may well justify the exception.¹⁵⁴ It is important to emphasize, however, that such intervention does not absolve the technology, once developed, of having to ultimately survive private competition in the free market.¹⁵⁵ Reducing access barriers to markets, as elaborated below, can also help incentivize innovation.

¹⁵⁰. Cockburn et al., supra note 2, at 5 (“While the private incentives for innovative investment in each application sector depend on its the market structure and appropriability conditions, that sector’s innovation enhances innovation in the GPT itself, which then induces subsequent demand (and further innovation) in other downstream application sectors.”).
¹⁵¹. Scotchmer, supra note 149, at 38.
¹⁵². For discussion of the benefits and shortcomings of governmental funding for the development of new technologies see, for example, CHRISTINE GREENHALGH & MARK ROGERS, INNOVATION, INTELLECTUAL PROPERTY, AND ECONOMIC GROWTH 313–18 (2010).
¹⁵⁴. See GARY E. MARCHANT ET AL., INNOVATIVE GOVERNANCE MODELS FOR EMERGING TECHNOLOGIES (2013). This is also done with regard to other technologies, most notably in recent years artificial intelligence. Regulatory intervention should, nonetheless, be careful to promote conditions for innovation while not picking winners. It should also be careful, flexible and cooperative, in order to ensure that governmental intervention is indeed justified. See id.
Interestingly, the market for 3D printing partially supplies its own solutions. A dedicated community of 3D technology enthusiasts already exists and is engaged in attempting to create better printers. Most notable is the RepRap project, an initiative to develop a 3D printer that could replicate itself. All of RepRap’s designs have been released under an open-source license, to be used by anyone so long as any changes made to the code are then also provided to those interested under a similar license. Yet, so far, such voluntary community-based innovations have been limited. Furthermore, the option of printing one’s own 3D printer might increase the potential for patent infringements, thereby reducing incentives to innovate, a point elaborated in the following Section.

**B. Removing Artificial Barriers to the Development of 3D Printers**

Even if 3D printing technology is optimally developed, to improve social welfare it needs to reach markets and consumers. Below, this Article identifies both private and government-erected barriers to accessing 3D printers.

Disruptive technologies, by their very nature, change the locus of profits and power. It is thus only natural that traditional manufacturers or assemblers are incentivized to erect artificial barriers to the use of 3D printers, thereby preventing or slowing down what

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of a certain type of innovation can change the course of the market. See MARCHANT ET AL., supra note 154 at 108.

156. Bechtold, supra note 7, at 524.


158. Id.

159. Bechtold, supra note 7, at 534.

160. Bechtold, supra note 7, at 530 (“These developments point towards a future of mass-scale infringement of 3D printing-related intellectual property rights by end-consumers with limited abilities of right owners to enforce their rights effectively.”).

161. Butenko & Larouche, supra note 135, at 54. Obviously, the expected height of entry barriers affects ex ante investment decisions explored in the previous Section. See Dasari, supra note 7, at 287.


163. This was recognized by Machiavelli. See NICCOLO MACHIAVELLI, THE PRINCE (Luigi Ricci trans.), reprinted in JEAN-PIERRE BARRICELLI, THE PRINCE: TEXT AND COMMENTARY: PRESENTATION AND ANALYSIS OF THE TREATISE ON POWER POLITICS 52 (1975) (“For the [innovator] has enemies in all those who profit by the old order, and only lukewarm defenders in all those who would profit by the new order, this lukewarmness arising partly from fear of their adversaries, who have the laws in their favour.”).
Schumpeter famously called “the process of creative destruction.”164 3D printer developers who enjoy first-mover advantages or control essential intellectual property rights might also attempt to erect artificial barriers to the entry of subsequent developers. Such barriers may come in multiple forms, including entering exclusionary long-term contracts, tying, imposing restrictions on the sale of relevant materials, or engaging in mass or exemplary litigation designed to create an exaggerated fear of using 3D printers, reminiscent of the Recording Industry Association of America’s campaign against music file sharing.165

Identifying and preventing the erection of artificial entry barriers is an important regulatory task. Here, antitrust laws play an essential role. By prohibiting anticompetitive agreements and monopolization, antitrust laws may prevent conduct that harms competition without offsetting benefits to consumers, such as long-term exclusivity contracts that extend beyond their procompetitive justifications.166

Furthermore, through their merger reviews, antitrust enforcement agencies may reduce the threat of limiting the ability of 3D printing technology to reach markets.167 The concern centers on what has come to be called “killer acquisitions,” acquisitions designed to stop technological developments in their tracks in order to preempt competition.168 Killer acquisitions have an unambiguously negative effect on consumer welfare, both through their stifling effect on competition and the elimination of innovative new products.169 Once reviewed, such mergers will generally be disallowed.170

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164. JOSEPH A. SCHUMPETER, CAPITALISM, SOCIALISM AND DEMOCRACY 82–85 (Routledge 2006) (1942) (this term refers to the market process by which new and more efficient suppliers upend the existing market structure and replace existing market players).

165. Wilbanks, supra note 42, at 1150, 1168.


167. See 15 U.S.C. § 18(a) (2000); HOVENKAMP, supra note 166, at 589–90. While the antitrust authorities possess the power to pursue mergers that do not fall within the guidelines for reportable deals, they rarely do so. HOVENKAMP, supra, at 497, 589.


169. Id. at 39. The overall effects of killer acquisitions on innovation may also be harmful: “Because killer acquisitions may motivate ex-ante innovation, the overall effect of such acquisitions on social welfare remains unclear. However, we think it unlikely that this acquisition channel, which generates significant ex-post inefficiencies resulting from the protection of market power, is the most effective way to motivate ex-ante innovation.” Id. at 41.

170. HOVENKAMP, supra note 166, at 492–94, 584.
Yet some killer acquisitions are currently not captured by merger law. This is because the law only captures mergers that meet a certain threshold of current turnover of the merging entities in the year preceding the merger. Accordingly, it does not apply to mergers with firms developing technologies that are still in the embryonic stage—that is, technologies that are not yet released to the market. Such mergers occur under the radar, despite their potential significant effects on competition and innovation. Furthermore, current law could strengthen incentives for some firms to delay exposing their technologies to the market in order to limit their current turnover and encourage other firms to acquire them before they fall within the scope of merger law.

Merger laws might therefore need to be changed. Indeed, it may be useful to follow the lead of Germany and Austria, which added to their laws the possibility of reviewing mergers based on the value of the transaction. The price paid for the technology then serves as an indirect indication of its worth to the acquirer. It may thus act not only as a benchmark for the need to review the proposed merger but also—as especially in horizontal mergers—as a rough signal for the expected effects of the technology in the eyes of the acquirer. Reviewing such mergers may be especially important in markets that have not yet fully matured, such as those related to 3D printing. Indeed, the industry is still at a stage where a large portion of its revenues are invested in research and development.
The government might also erect barriers to accessing or expanding 3D printing. 3D printers raise serious societal concerns, such as those pertaining to product quality and the creation of purposefully harmful products. Assume that a house builder can design and print his own staircases. How can the government ensure that such staircases are safe and will not harm their users? As the market for home or local printers develops, the public is bound to call for placing greater limitations on the use of 3D printers. Furthermore, as observed above, one major issue involves the influence of 3D printers on the incentives for product designers to innovate due to intellectual property theft. This issue has justly generated much attention, and different solutions have been proposed.

One suggestion involves protection-by-design, where a predetermined signal that the design is protected by an intellectual property right is embedded in the software, and the printer automatically detects the signal and prevents printing unless the user disables the signal by paying for the right of use. Another proposed solution is to encrypt CAD files. Yet when the physical product can be accurately copied by using images or a 3D scanner, the above solutions are only partially effective. Other proposed solutions involve ex post tracking. By way of analogy, to uncover counterfeit printing, some manufacturers of traditional printers have collaborated with the government and designed their printers to print “digital watermarks”—microscopic yellow spots personalized to the machine—on every document. These spots enable law enforcement


180. For such calls see, for example, Bechtold, supra note 7, at 530–31; Brean, supra note 7, at 772; Desai & Magliocca, supra note 7; Li, supra note 7, at 13–15, 21; Luczkow, supra note 7, at 1159.

181. See Luczkow, supra note 7, at 1158–59; see also discussion supra Section III.C.

182. See discussion immediately below.


185. Berkowitz, supra note 183, at 78–79.

186. Id.
agencies to track a copied document back to a particular printer. However, this solution raises surveillance concerns. Furthermore, solutions that interfere with the design of printers may overburden the industry and stifle innovation. Additionally, the unique characteristics of the 3D printer itself, in particular its ability to print a new 3D printer, could frustrate this solution. For the same reasons, it may be ineffective to compensate designers through the imposition of a surcharge on those buying the machinery that enables the infringement, as was done with CD burners, which could be used to illegally copy media content.

The threat of being held as facilitators of intellectual property infringement increases the incentives for printer manufacturers to find technological solutions to infringement concerns. This threat is further strengthened by the concern that designers will have suboptimal incentives to invest in designs for 3D printers or that overprotective regulation will be imposed on the industry should it not adopt its own solutions. Indeed, some manufacturers are experimenting with some of the methods noted above, including labeling techniques and enabling only identified files to be printed. Another market solution involves a “pay-per-print” business model, in which CAD files are sent directly to the 3D printer through a secure streaming interface. The printer then prints out the number of objects that have been purchased. This solution is already in operation by companies

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187. Id. Berkowitz claims that to implement a similar system for 3D printing would be difficult since manufacturers would need to develop a “spot” for every type of material that could be used in a 3D printer. Id.

188. Id. at 79.


190. REPRAP PROJECT, supra note 157.


192. 3D printing technology could challenge definitions of infringement of intellectual property rights. If, for example, one takes a picture of a physical object, turns it into a CAD file, alters it to his needs by adding new features, and prints the object, under what conditions should this hybrid creation be considered an infringement?

193. Bechtold, supra note 7, at 531.


195. Id.
such as Authentise and Secure3D and can be particularly effective for the customized goods industry.\textsuperscript{196} Yet so far, such solutions have only been partially adopted.

Undoubtedly, guaranteeing that designers of new products have sufficiently strong incentives to innovate is one of the greatest challenges created by 3D printing and its complementary technologies.\textsuperscript{197} At the same time, it is important to ensure that solutions go no further than what is needed to set the correct incentives in the market and that sufficient weight is given to the positive effects of the technology.\textsuperscript{198}

This concern is particularly notable because the risks created by 3D printing technology are easily understood and therefore can strike a chord with the public as well as with regulators.\textsuperscript{199} Those arguing for governmental regulation may tend to downplay the benefits of 3D printing.\textsuperscript{200} Indeed, many of those writing on copying concerns raised by 3D printing technology have not mentioned or given much weight to the factors that mitigate the possibility of piracy, which are identified above, some of which arise from the properties of 3D printing itself.\textsuperscript{201} Furthermore, given the high private costs of disruption, those market players negatively affected by the change could attempt to exploit such concerns in order to influence the lawmakers to overregulate, which does not serve social welfare.\textsuperscript{202} Also, the fact that the disruption is expected to be significant and multifaceted may lead overly cautious

\textsuperscript{196} Id.
\textsuperscript{197} See, e.g., Bechtold, supra note 7, at 531; Brean, supra note 7, at 782; Desai & Maglioeca, supra note 7, at 1694; Li, supra note 7, at 20; Luczkow, supra note 7, at 1158–59.
\textsuperscript{198} CHARLES WOLF, JR., \textit{A THEORY OF 'NON-MARKET FAILURE': FRAMEWORK FOR IMPLEMENTATION ANALYSIS}, 2, 22–25 (1978). Wolf argues that government failure may be of the same magnitude as market failure. \textit{Id.} at 10.
\textsuperscript{199} For a similar argument with regard to intellectual property infringements, see Nicole A. Syzdek, \textit{Five Stages of Patent Grief to Achieve 3D Printing Acceptance}, 49 U.S.F. L. REV. 335, 342, 348 (2015).
\textsuperscript{200} See, e.g., Desai & Maglioeca, supra note 7, at 1702; Luczkow, supra note 7, at 1158–59.
\textsuperscript{201} See Brean, supra note 7, at 781.
regulators to intervene in order to protect the status quo. It thus becomes essential to ensure that competition and innovation considerations are not disregarded and that other interests are not given too much weight, thereby creating unnecessary barriers to the development and dissemination of 3D printing.

Let us venture even further: the change brought about by 3D printing may challenge assumptions regarding the extent of intellectual property rights protection needed to ensure dynamic efficiency. This is because, as suggested above, while 3D printing makes copying some products easier, it also reduces the extent of sunk costs as it reduces design and manufacturing costs. This reduction may challenge the economic basis for the existing scope of intellectual property rights. Indeed, when determining the scope of these rights, it might be more efficient to evaluate designs based on their sunk costs and the ease of copying them.

It is suggested that, where possible, antitrust authorities take an active advisory role in such regulatory and legislative processes, to ensure that the right balance is reached. Antitrust authorities have two main comparative advantages to offer over other regulatory bodies. First, they possess significant expertise and experience in analyzing the competitive impact of a wide range of technologies, market conditions, and conduct. Second, they are often less susceptible to political pressures than legislatures and sector-specific regulators, due in part to the fact that antitrust is not sector-specific and they are independent regulatory agencies. This is not to say that they are completely shielded from political pressures—but they are often less likely to yield to them.

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203. Lemley & McKenna, supra note 202, at 6–7.
204. By way of analogy, calls for (de)regulating the sharing economy are sometimes imbued with the interests of interest groups, which do not reflect the joint social interest. See, e.g., Michal S. Gal, The Power of the Crowd in the Sharing Economy, 13 L. & ETHICS HUM. RIGHTS 1, 13, 15 (2018).
205. See Beneke, supra note 87.
207. For the advisory role of competition authorities see, for example, OECD, RELATIONSHIP BETWEEN REGULATORS AND COMPETITION AUTHORITIES, 189, 262, 266 (1999), http://www.oecd.org/dataoecd/35/37/1920556.pdf [https://perma.cc/MX6V-C3GW]. For an overview of the literature on how the characteristics of regulators affect their ability to serve the public interest see, for example, Butenko & Larouche, supra note 135, at 78–79, 82.
209. Id. at 8–9; OECD, supra note 207, at 8, 21, 23.
211. Id. at 10.
While antitrust authorities should play an advisory role, they should not make the ultimate decisions. They do not possess the knowledge and tools needed to evaluate all the implications for social welfare and to balance competing considerations. In addition, they may not be the appropriate vehicle to make broad policy decisions that could carry social, political, or cultural consequences that are not within their democratic mandate. Yet consultation with legislatures or regulators on legislative and regulatory procedures that impact 3D printing technology may have a direct impact on the normative environment by limiting unnecessary barriers to competition. The consultation process should be made public in order to create a basis for a public debate regarding competition and innovation considerations. Such a debate will limit the incentives and ability of legislators and regulators to make decisions against the public interest.

C. Combating Monopolization in the 3D Printing Supply Chain

A third set of concerns focuses on monopolization of any link in the 3D printing supply chain. Such concerns differ from the previous two explored above that focus on obstacles to the entry of 3D printing into markets. This Section assumes that such printers have indeed succeeded in doing so and focuses on the conduct of the suppliers of this technology. A monopolistic supplier of 3D printing technology might use his significant market power in order to erect artificial barriers to the entry or expansion of competitors, thereby stifling competition and innovation and reducing welfare.  

3D printing technology affects the concentration of market power. The “leaner” supply chain created by 3D printing implies that the number of links that can enjoy market power is smaller relative to traditional industries. Furthermore, some links in the new supply chain are likely to be highly competitive, decentralizing power rather than strengthening it. This is especially true with regard to the design segment, given the ease of microentry and exit, as well as the increased ability of consumers to design some products themselves by using 3D-printing-related technologies. Likewise, the reduction in asset

212. Id.
213. Id. at 11.
215. HOVENKAMP, supra note 166.
216. See id.
specificity reduces the emergence of market power in the production and assembly segments, at least with regard to some goods.

Significant market power could arise, nonetheless, in other parts of the supply chain. For example, providers of unique 3D printers or inks may enjoy significant and persistent comparative advantages. In this respect, it is important to emphasize that 3D printers may differ in the technology they use for layering and binding and the materials that can be used by them. To illustrate, printers that can work with titanium enjoy significant comparative advantages in the production of some products. The lower asset specificity of 3D printers could extend providers’ market power to many markets simultaneously.

As 3D printing develops, so too will the role of intermediaries that connect product designers and users (also called design platforms), like in other digitized markets, such as short-term rentals and music downloads. Indeed, firms like Thingiverse, Sculpteo, and Shapeways already operate digital platforms where 3D designs are sold or shared. Such design platforms facilitate transactions in many ways, including by providing information (e.g., how to use the technology, options, ratings, and suggestions), managing risk, connecting designers and users, and even setting prices. Their role will become essential, at least with regard to some goods, given the expected abundance of designs.

The question is thus whether some design platforms are expected to enjoy considerable advantages over their rivals and thereby build up significant market power. Advantages may arise, for example, from economies of scale and two-sided network effects; design

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217. Yet such market power could be reduced by the fact that the personal 3D printing market is characterized by many “user-innovators” who are not mere consumers of a product but are also able to alter and improve upon existing open-source hardware and software designs. See Samuelson, supra note 81, at 564.


219. For the role platforms play in many digital markets see Julie E. Cohen, Law for the Platform Economy, 51 U.C. DAVIS L. REV. 133, 135, 149 (2017) (“The platform is not simply a new business model, a new social technology, or a new infrastructural formation (although it is also all of those things). Rather, it is the core organizational form of the emerging informational economy.”).

220. Bechtold, supra note 7, at 525.

221. SUNDARARAJAN, supra note 1, at 78 (giving a positive answer to this question).

222. Thingiverse, for example, has 460,000 design files. Shapeways had, in 2014, nearly 500,000 3D objects. See Bechtold, supra note 7, at nn. 33–34.

223. SUNDARARAJAN, supra note 1, at 57.
platforms that offer more designs might attract more users, which in turn may attract a larger number of designers.\textsuperscript{224}

The characteristics of 3D printing technology could either decrease or increase a platform’s comparative advantages. On one hand, the ease of microdesign, which may exponentially increase the number of designs available, coupled with the increased ability of users to alter some product features to their liking may reduce the comparative advantages of any particular design and, resultantly, those of the design platform which offers it. On the other hand, the abundance of designs could reduce users’ incentives to multihome—that is, to seek designs on several platforms in parallel.\textsuperscript{225} Indeed, too much choice might not necessarily be appealing to users, as it can create cognitive overload and increase psychological burdens on consumers.\textsuperscript{226} This, in turn, implies that first movers have a comparative advantage\textsuperscript{227} because the user might get used to them and avoid switching due to choice overload.

This begets the question regarding the source of a comparative advantage of a design platform. The number of available designs is relevant, although, as shown, economies of scale are not boundless. Comparative advantages may be based on factors such as better imaging technology, which can indicate how the finished product will look, or better design capabilities, which make it easier for users to alter existing designs to their own liking. In many digital platforms, comparative advantages are based on data.\textsuperscript{228} To a certain extent, the same can be expected from design platforms. Platforms that possess better data on data subjects’ preferences might be better positioned to suggest products to users. Such data advantages may grow over time; a platform that establishes an advantage at an early stage may use it to generate even more data about consumer preferences. This may erect a barrier to entry for rivals and potentially lead to lock-in and anticompetitive conduct.\textsuperscript{229} Yet it is not clear that such data-based advantages will be significant, especially when self-design

\begin{itemize}
\item \textsuperscript{225} Evans & Schmalensee, supra note 224.
\item \textsuperscript{226} Discomfort and anxiety often accompany the shopping process. Elizabeth Nixon & Yiannis Gabriel, ‘So Much Choice and No Choice at All?’ A Socio-Psychoanalytic Interpretation of Consumerism as a Source of Pollution, 16 Marketing Theory 1, 13 (2015).
\item \textsuperscript{228} Maurice E. Stucke & Allen P. Grunes, Big Data and Competition Policy (2016).
\item \textsuperscript{229} Id.
\end{itemize}
alterations—rather than the original design of the product—play an important role in the user’s preferences.

3D printing also affects the ways in which market power can be monopolized and the ability to regulate such conduct. Monopolization arises when a firm with significant market power erects barriers to competition that are not based on the monopolist’s comparative advantages without offsetting benefits to consumers.230 Such conduct might include predatory pricing, exclusivity contracts, and tying.231 While such concerns are not unique to 3D printing, the characteristics of the technology affect the feasibility of monopolizing. This is illustrated by tying.

3D printing affects the form of tying. This is because, in some cases, technological tying can be overcome by printing the unique product on the 3D printer itself. The reduced ability to engage in successful technological tying, in turn, encourages firms to seek alternative ways to tie.

The characteristics and current state of 3D printing technology also affect the welfare analysis of tying conduct in several ways. 3D printing technology raises three unique justifications for tying. First, the bounded rationality of potential users, as well as their limited awareness of the benefits of the technology, increases the need for adopting business models that will intensify the dispersion and the resulting development of 3D printing technology. In the case of tying, this need may be intensified by the reduction in asset specificity, which implies that not all uses across industries can be recognized or contracted for ex ante. Tying of the ink or of designs may enable manufacturers to sell the printers at low cost while differentiating among consumers based on their actual use of the printer, thereby increasing the use of 3D printing technology. Second, as Bechtold suggests, given the increased possibility of infringement of patents relating to 3D printers (due to the ability to copy a printer by printing it), manufacturers may shift to business models that enable them to sell printers at a price which limits incentives to illegally copy them while covering their costs through the price of complementary products over which they may enjoy some more control.232 Third, the risk that 3D printer manufacturers will be legally regarded as facilitators of copyright infringement with regard to products printed

230. For tests that capture such conduct see, for example, Einer Elhauge, Defining Better Monopolization Standards, 56 STAN. L. REV. 253, 264 (2003); John Vickers, Abuse of Market Power, 115 ECON. J. 244, 245, 252 (2005).

231. See, e.g., HOVENKAMP, supra note 166.

232. Bechtold, supra note 7, at 531.
on their printers increases the incentives for such manufacturers to find ways to limit such a risk. Absent business models that can deal with the above three considerations, the development of 3D printing technology might be suboptimal.

On the other hand, tying might slow down the development of materials for 3D printing. By potentially reducing the incentives of firms that do not sell 3D printers to engage in materials research and development, tying might impair advancements in 3D printing. This, in turn, implies that the analysis of tying concerns should not focus solely on the market for 3D printers or its complementary goods but should be based on the overall effects of the conduct on innovation in 3D printing and even on wider manufacturing markets. It also strengthens the need for ensuring that the procompetitive effects of tying cannot be achieved through less restrictive means.

Accordingly, to ensure efficient innovation and diffusion of 3D technology, regulators must counteract the monopolization of market power while encouraging its unique positive effects on welfare.

V. CONCLUSION

As 3D printing technology develops, it holds promise to change many aspects of the global economy. This general-purpose technology will impact internal and external business structures, productivity, innovation, growth, trade, employment, population dispersion, and even wealth inequality. By offering new or higher quality products, customized to each consumer’s needs, at lower cost and with faster delivery, it also increases consumer welfare.

Given these expected changes, it is important to identify the challenges to the growth and diffusion of 3D printing technology and develop institutions and a policy environment that are conducive to such manufacturing in a way that promotes competition and social welfare. This Article focuses on one important piece of this puzzle: challenges to competition and innovation. It identifies three main challenges and suggests regulatory tools that can be used to deal with them. Unless we take such steps, we might not enjoy the full and vast benefits that 3D printing technology has to offer.