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Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited

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ABSTRACT

Additive manufacturing (AM), colloquially known as 3D printing, is currently being promoted as the spark of a new industrial revolution. The technology allows one to make customized products without incurring any cost penalties in manufacturing as neither tools nor molds are required. Moreover, AM enables the production of complex and integrated functional designs in a one-step process, thereby also potentially reducing the need for assembly work. In this article, we discuss the impact of AM technology at both firm and industry level. Our intention is to discern how market structures will be affected from an operations management perspective. Based on an analysis of established economic models, we first identify the economic and technological characteristics of AM and distill four key principles relevant to manufacturers at firm level. We then critically assess the effects of AM at industry level by analyzing the validity of earlier assumptions in the models when these four principles apply. In so doing, we derive a set of seven propositions which provide impetus for future research. In particular, we propose that in a monopoly, the adoption of AM allows a firm to increase profits by capturing consumer surplus when flexibly producing customized products. Meanwhile in competitive markets, competition is spurred as AM may lower barriers to market entry and offers the ability to serve multiple markets at once. This should ultimately result in lower prices for consumers.

1. Introduction

Research has shown that technological innovation affects firms and market structure (Mills and Schumann, 1985; Vickers, 1986; Geroski and Pomroy, 1990; Khanna, 1995). In particular, the adoption of flexible manufacturing systems (FMS) has had significant implications for manufacturers and market structure (e.g., Sethi and Sethi, 1990; Womack et al., 1991). FMS can flexibly produce a variety of different outcomes using the same (manufacturing) resources (Gerwin, 1993). More recently, research has highlighted the potential of additive manufacturing (AM) technology to spark a new industrial revolution by extending the features of conventional FMS technology (The Economist, 2011, 2012; Berman, 2012; Mellor et al., 2014). AM refers to “the process of joining materials to make objects from 3D model data, usually layer upon layer” (ASTM International, 2013). Colloquially, AM is often referred to as “3D printing” (Lipson and Kurman, 2013). The main benefit of AM technology is that it enables the flexible production of customized products without cost penalties in manufacturing. It does so by using direct digital manufacturing processes that directly transform 3D data into physical parts, without any need for tools or molds. Additionally, the layer manufacturing principle can also produce functionally integrated parts in a single production step, hence reducing the need for assembly activities. Thus, AM technology significantly affects the costs of flexibility, individualization, capital costs, and marginal production costs (Koren, 2006; Dolgui and Proth, 2010; Berman, 2012). While AM could simply be interpreted as a new generation of conventional FMS, earlier research has argued that its economic characteristics are so different that investment decisions into AM are highly strategic (Mellor et al. 2014). Nonetheless, the opportunities of AM still come with a number of limitations: available materials do not always match the characteristics of conventional manufacturing processes, the production throughput speed is rather low, most manufactures still demand an additional surface finish, and common standards for quality control are not established yet (Berman, 2012). Given this trade-off, one motivation of our paper is to provide support in evaluating a firm's specific manufacturing context before potential investments in AM technology.

Additionally, AM technology affects market structure beyond direct effects on a single firm's production processes. There is a growing community of “makers” who develop and share 3D models, sell 3D printed products on marketplaces, and even develop and provide their own 3D printers for home usage

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(Gershenfeld, 2005; Lipson and Kurman, 2010; de Jong and de Bruijn, 2013). Furthermore, a steadily growing number of 3D printers for home and industrial use extends the scale and scope of manufacturing options. AM technology is even on the political agenda, with U.S. President Barack Obama promoting AM as having "the potential to revolutionize the way we make almost everything" (Obama, 2013). Only two years ago, industry analyst Gartner (2012) argued that AM is at its "peak of inflated expectations," noting that the technology is still too immature to satisfy such high expectations. More recently, however, Gartner (2014) predicted that industrial use of AM is likely to reach a level of mainstream adaptation between 2016 and 2020.[1]

Various early adopters demonstrate AM's potential benefits for firms in different markets. In the shoe industry, for example, manufacturers have been using AM technology for many years to rapidly test new designs and accelerate the innovation process (Jopson, 2013). But today, customized end products are also manufactured with AM. For example, *Nike* offered a customizable football cleat produced with AM in 2013. At the same time, AM technology also facilitates market entry into a relatively mature industry. For example, the Belgian shoe retailer *Runners Service Lab* offers affordable, customized running shoes produced with AM technology. As a demanding industrial application consider the usage of AM in the aerospace industry, where the elimination of many conventional design-for-manufacture constraints promises opportunities for optimized designs to increase performance and reduce weight of components. Despite the high regulatory requirements, AM has already been used for the low volume production of aerospace components. *Boeing* uses some thermoplastic components produced with Selective Laser Sintering technology on commercial 737, 747 and 777 programs and has several hundred components on the 787 aircraft prototype (Mellor, 2014). Further industrial applications of AM are frequent in medical markets, defense, automotive and machinery components (Wohlers, 2013).

Despite the current "AM hype", research on the economic and business effects of AM technology is still scarce. Most academic literature on AM is focused on the technological aspects in the fields of engineering, material science, and computer science. Therefore, our paper aims to outline some central potential economic implications of AM on manufacturing firms and markets. We acknowledge that our assessment is futuristic to some degree. AM is currently mostly applied on a small scale in niche markets or in a lab environment. No large-scale empirical data is yet available to test our propositions. However, current research continues to enhance the capabilities of AM technology. Industry experts claim that its maturity will lead to a broad industrial penetration within the next few years (Lux Research, 2013; Wohlers, 2013; Gartner, 2014).

This is why an economic assessment and an evaluation of business implications are crucial. Our work aims to initiate this academic discussion. By relying on established production economic models as the basis of our analysis, we strive to ground our arguments beyond any hype or speculation. Doing so, we contribute to the existing literature in four ways. Firstly, we distill four key principles of AM relevant to manufacturing firms, and systematically evaluate their potential effects on a firm's payoff function (in a monopolistic setting), applying Milgrom and Roberts' (1990) model of modern manufacturing on AM. Secondly, we analyze extant literature containing market structure models that assess advancements in the flexibility of manufacturing systems along the dimensions of AM technology's key principles, investigating the effect of AM on competition at industry level. Based on our analysis we then develop a set of seven propositions as an impetus for future research on the economic implications of AM technology. Fourthly, we outline relevant implications for industrial practitioners by summarizing AM's technological opportunities, applications, and constraints. Our article proceeds as follows: Section 2 presents an overview of AM technology and its economic characteristics. Section 3 investigates the effects of adopting AM at firm level, while Section 4 derives implications for market structure at industry level. Finally, we present conclusions and implications for future research.

2. AM characteristics and key principles for manufacturing firms

2.1. Technological background

AM technology has been in use since the 1980s. Its early application was limited to the production of prototypes. The technology's primary goal was to offer a quick and affordable way to receive tangible feedback during the product development process. Primarily, the stereolithography method was used to harden liquid photo-sensitive polymers with laser light in a layer-by-layer process (Gibson et al., 2010). This production of prototypes has become common practice in many firms and industries and is not the object of our investigation. The far greater opportunities of AM are in replacing conventional production technologies for series manufacturing ("rapid manufacturing", Gibson et al., 2010). This application is the object of the current hype and debate. It includes the production of parts and components, but also the manufacturing of end products. Market expert Terry Wohlers forecasts that end products will account for 80 percent of the total AM production output by 2019 (Davidson, 2012). The availability of materials for AM has increased steadily over the last years, ranging today from various plastics to ceramics, metals and concrete – basically, any material that can be liquefied/melted and re-solidified (Gibson et al., 2010).[2]

AM offers several technological advantages that enhance conventional FMS. First of all, AM enables direct manufacturing of digital 3D models stored in a computer-aided design (CAD) file, without the need for tools or molds (Gibson et al., 2010). AM is therefore a prototypical example of a flexible manufacturing technology, as it conceptually enables a vast variety of outcomes in manufacturing in any given sequence on one stable manufacturing system (Berman, 2012). Other than consumables (materials) and the actual AM machine, only the product's digital 3D model is necessary for manufacturing (Gebhardt, 2003). Setup and changeover costs are negligible as only a different CAD file needs to be uploaded into the machine when changing the product to be manufactured – neither tools nor molds are necessary (Petrovic et al., 2010). As a result, AM enables product individualization without cost penalties (Gibson et al., 2010). By adding material layer by layer until the product is finalized, AM has fewer process and design restrictions; it therefore also allows for functionally optimized product designs (e.g., lightweight designs, integrated cooling chambers) (Petrovic et al., 2010; Lott et al., 2011). Furthermore, an increase in design complexity does not mean higher production

[1] Indications of market confidence in the sustainability of business models relying on 3D printing offerings include the recently announced acquisition of the 3D home printer manufacturer and operator of the Thingiverse platform, Makerbot, by Stratasys for US$403 million (Stratasys, 2013). Furthermore, dedicated investment funds have been launched that track the performance of the AM sector which also indicates the growing importance of this industry.

[2] Ongoing research activities also enhance specific AM technologies for printing human tissue, as provided for example by the California-based company Organovo, or for printing edible substances (3D Systems, an AM machinery provider, recently launched a "food 3D printer", enabling chefs and bakers to produce customized edible arrangements).