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// JULIAN SCHWIERZY AND TOBIAS WENZEL

Mass Customization With Additive Manufacturing: Blessing or Curse for Society

Mass customization with additive manufacturing: blessing or curse for society?

Julian Schwierzy[1,*] Tobias Wenzel[2,3,†]

[1]Technical University of Munich
[2]Düsseldorf Institute for Competition Economics (DICE)
[3]ZEW Mannheim

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Abstract

Additive Manufacturing (AM) enables mass customization and has thereby the potential to revolutionize traditional manufacturing. In this paper, we examine how the adoption of AM affects competition and welfare in traditionally standardized product markets. Analyzing a game-theoretical model of spatial product differentiation, we find a decline in standardized product prices. In contrast, the price of customized products will exceed the price level of the initial market. These price changes are accompanied with a reduction in the number of traditional manufacturers. In terms of welfare, AM adoption increases total surplus. However, it can be detrimental for consumer surplus if the competitive advantage of AM technology is excessively large. Based on these findings, we discuss policy implications for the manufacturing industry. We recommend complementary measures of ensuring the competitive environment for firms with AM technology and subsidizing their fixed cost in order to realize benefits for both consumers and producers.

Keywords: Technology adoption, Market structure, Welfare, Product differentiation, Industrial Additive Manufacturing

JEL codes: L11,L22,L23,O33

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[*] Email: julian.schwierzy@tum.de. Address: Technical University of Munich, TUM School of Management, Arcisstr. 21, 80333 München, Germany.

[†] Email: wenzel@dice.hhu.de. Address: Düsseldorf Institute for Competition Economics (DICE), University of Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany.

1 Introduction

The adoption of new technology serves as a catalyst for both economic growth and paradigm shifts within and across industries (Romer 1990, Aghion et al. 2021). In recent decades, digital technologies have not only disrupted traditional market landscapes but have also unlocked new avenues for innovation and competition (Goldfarb & Tucker 2019). This digital revolution requires attention from economists, industry managers, and policymakers in order to exploit its full potential for societal advancement.

Within the domain of technological innovations, Additive Manufacturing (AM), commonly known as 3D printing, is a key driver in propelling the digitalization of the manufacturing sector. AM has drawn significant attention in recent literature, with discussions centered around its implications for production efficiency, supply chain dynamics, and reshaping market structures (Weller et al. 2015, Baumers et al. 2016, Kunovjanek et al. 2022). While its usage has mainly comprised rapid prototyping, AM is evolving in its applications to produce final products (Campbell et al. 2023). Besides the advantages of manufacturing sustainable and complex products, AM unlocks the potential for product customization at a large scale (Gibson et al. 2014). Manufacturers in several industries have already adopted this digital technology to meet diverse consumer needs by offering customized products. For example, medical professionals utilize 3D-printed implants, prosthetics, and splints that conform precisely to a patient's body providing a better support for rehabilitation.

In recent years, AM has been diffusing into traditionally standardized product markets. A prime example is the market for bike and football helmets. There, consumers can choose between helmets with standardized sizes or customized sized helmets from companies using AM, such as HEXR and Vicis. A well-fitted helmet can significantly enhance the user experience and minimize injury risks. It is therefore not surprising to see many professional football players opting for customized 3D-printed helmets.[1][2] AM's diffusion and the increasing availability of customized products could dramatically transform the competitive landscape, changing how products are differentiated and priced. Despite these possible developments, the broader implications of AM adoption remain largely unexplored, especially in terms of welfare and the need for policy interventions.

The purpose of this paper is to investigate the influence of adopting industrial AM for product customization on market structure and welfare. By analyzing market structure,

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[1] For anecdotal evidence, see the following article.
https://www.forbes.com/sites/carolynschwaar/2023/10/01/nfls-safest-helmets-absorb-impact-with-3d-printing-instead-of-foam/?sh=7e3d6fe678e7

[2] Another example represents the customization of robot grippers in the automotive industry.
https://www.press.bmwgroup.com/global/article/detail/T0442351EN/bmw-group-expands-use-of-3d-printed-customised-robot-grippers?language=en

we focus on the number of firms in the market and their pricing strategies, depending on the competitive advantage and competitive environment of the AM technology. Drawing on established game-theoretical models of product differentiation (among others Salop 1979), we examine a spatial model.

Following the approaches of Balasubramanian (1998) and Kleer & Piller (2019), our model describes competition between companies with traditional manufacturing (TM) technologies offering standardized products and companies with AM providing customized products, a scenario likely to unfold in the future. Wohlers (2023) suggests that AM acts as a complementary technology to TM, particularly in the production of final products. AM is not expected to replace TM for low-volume and simple geometric parts due to cost implications for large-scale production. In our base model, only one firm adopts AM due to risk of Bertrand competition and marginal cost pricing for potential competitors utilizing the same technology.

The resulting market equilibrium indicate lower prices for standardized products compared to a market without the existence of AM technology. Yet, the price of the new introduced customized products exceeds the level of markets with only standardized products. Furthermore, the model results show a negative correlation between the competitiveness of the AM technology and the number of TM firms. In other words, more firms utilizing TM technology leave the market as the AM technology improves over time (e.g. through a decline in production costs). This effect is mainly attributed to an increased market power of the firm with AM technology.

In the welfare analysis, we show that the adoption of AM benefits consumers when the number of TM firms remains constant. However, this finding may not hold when considering the endogenization of firms' market entry. Consumer surplus depends on the number of TM firms and, therefore, declines with an increasing competitive advantage of AM technology. We identify a critical level of the competitive advantage beyond which AM adoption becomes detrimental for consumers. However, AM adoption raises total surplus by increasing competition. This analysis implies harmful effects for consumers if governments implement policies fostering AM's competitive advantage even though it is boosting total surplus. Nevertheless, we show that subsidizing fixed costs can raise both consumer and total surplus if it induces AM adoption.

In our base model, the increased market power of the AM firm plays a critical role in the welfare outcomes. Therefore, we extend our model to include competition with potential rivals for the AM firm. Intensified competition for the AM firm leads to two main implications. On the one hand, competitive pressure drives down effective prices for customized products, thereby benefiting consumers. On the other hand, AM entry becomes less likely. Therefore, promoting AM competition may require subsidies to incentivize the adoption of AM technology and ensure the highest possible level of consumer surplus.

The analysis and findings of this paper are important for at least three reasons: First, AM plays an increasingly important role in firm's serial production. Revenues of the global AM market for products, and services has grown at a compound annual growth rate of roughly 25% between 2010 and 2020. While the market size encompassed \$1.3 billion USD in 2010, the size grew to \$12.8 billion USD in 2020, and resulted in an overall value of \$18 billion USD in 2022 (Campbell et al. 2023). This development is in line with the growth of international patent families (IPFs) for AM. According to Cavallo et al. (2023), the number of IPFs increased from 1,576 in 2013 to 8,090 in 2020. In addition, the number of startups using AM for the production of goods has increased in absolute and relative terms compared to startups developing hardware, software or material solutions (Campbell et al. 2023). These developments demonstrate the relevance of AM for the manufacturing sector suggesting that our discussed changes in competition will occur more frequently and become more prevalent.

Second, governments actively promote digitalization by providing funding programs. These programs typically support research & development or technology acquisition reducing marginal cost and fixed cost. There are various AM tailored programs to foster its adoption. In Europe, the European Commission provides R&D funding for AM within the framework of the Horizon program helping to achieve the UN's Sustainable Development Goals and boosts the EU's competitiveness and growth. In the United States, the government provides access to capital for small & mid-size enterprises in order to sustain high-paying jobs and improve supply chain resilience.[3] With our analysis, we shed light on the effectiveness of these programs and provide implications for an efficient design.

Third, the results of our model can be applied to other technologies and applications, e.g. the rise of smart factories and supply chain flexibility. Several digital technologies reduces transportation costs and enable, thereby, a decentralized production (Goldfarb & Tucker 2019). In other words, the production occurs close to consumer's location instead of in central manufacturing hubs. Our model allows to reframe the interpretation of the spatial dimension and to consider a geographical perspective. Therefore, we can also draw conclusions for the competition between centralized and decentralized factories among other examples.

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[3] See e.g. https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/06/fact-sheet-biden-administration-celebrates-launch-of-am-forward-and-calls-on-congress-to-pass-bipartisan-innovation-act/

2 Literature review

This paper builds on research in the domain of industrial organization and draws from literature in digital economics, spatial product differentiation, flexible manufacturing, and additive manufacturing. A brief discussion of insights from these research fields provides an overview of the relevant literature as well as illustrates the research gap and our contribution.

Research in digital economics examines how digital technologies affects economic activities (Goldfarb & Tucker 2019). Among others, studies in this field are interested in the competition between offline versus online marketplaces (Forman et al. 2009), physical versus digital products (Pattabhiramaiah et al. 2022) and its impact on consumer surplus (Brynjolfsson et al. 2003). A common approach to model this kind of competition are spatial models (Balasubramanian 1998, Bouckaert 2000). Most spatial models based on the groundwork of a linear street (Hotelling 1929) or circular city (Salop 1979) and were constantly improved over the last years, e.g. Bar-Isaac et al. (2023). With our study, we contribute to this stream of literature by investigating the competition between firms with TM technology and firms with AM technology, a digital manufacturing technology, and the resulting consequences for welfare.

Until the late twentieth century, manufacturing facilities were specialized to produce standardized products in large quantities in order to realize economies of scale. The rise of information technology has opened up new opportunities for the manufacturing industry with respect to its flexibility. Firms have been provided with the opportunity to adopt flexible manufacturing (FM) technologies and thereby increase their product variety (Milgrom & Roberts 1990). Due to the capability of AM technology to flexible manufacture products, it can be categorized as a FM technology (Eyers et al. 2018). AM encompasses a group of production technologies combining material, energy, and digital data of the product design to create a physical product in a layer-upon-layer process (Gebhardt & Hötter 2016). Conversely to TM technology e.g. injection moulding, AM technology utilizes CAD-models and do not require any product-specific tools, moulds, or preparations for the production of goods (Gibson et al. 2014). Hence, it reduces the cost penalty for flexibility and provides the opportunity to extend product variety without significantly compromising cost efficiency. Furthermore, the reduction of flexibility costs allows firms to realize economies of scope (Baumers & Holweg 2019).

Economic literature discusses the consequences from the adoption of FM for market structure and welfare (von Ungern-Sternberg 1988, Eaton & Schmitt 1994, Alexandrov 2008), especially in terms of mass customization (Dewan et al. 2003, Bernhardt et al. 2007). Some studies discuss firms' incentives to adopt FM technology. Röller & Tombak (1990) show how the choice of technology differs under varying market structures and conclude that firms are more likely to adopt FM in larger markets, in markets with a high degree of product differentiation, and few competitors. Chang (1993) argues that its adoption has the purpose of hedging markets with demand uncertainty and deterring potential market entries. Based on an entry game, he shows that an incumbent threatened by a potential entry is more likely to adopt FM technology if the variability in consumer preferences is high. In line with this result, we find a higher likelihood of AM adoption if consumers have a strong preference for differentiated products. Moreover, we show the importance of AM's cost structure, competitive environment, and consumers' customization involvement cost for the technology adoption decision.

The adoption of FM technology has tremendous implications for the competition intensity in markets with differentiated products. The capability of FM to flexibly manufacture various product variants lowers the unique positioning of products and therefore firm's market power. Hence, the adoption of FM technology leads to a tougher price regime and a higher level of market concentration (Eaton & Schmitt 1994, Norman & Thisse 1999). Norman & Thisse (1999) show that the production flexibility of FM technology allows a change in the price of one product variant without changing others because of the capability to manufacture products that perfectly match with consumers' preferences. Therefore, firms with FM are not committed to a set of prices and can more easily change their pricing strategy to deter potential entrants. Concordant to these findings, our results indicate increased competition by a decline in the number of firms with TM technology and a reduction of standardized product prices. Furthermore, only one firm adopts AM technology and deters competitors to adopt the same technology. Surprisingly, the AM firm exhibits the capability to charge a premium price for its customized products.

More ambiguous are the consequences for welfare especially consumer surplus. According to Röller & Tombak (1990), consumers always benefit from the adoption of FM technology. In contrast, the model of Eaton & Schmitt (1994) indicates the risk of negative implications for consumers due to higher market concentration. The effect on consumer surplus depends on the elasticity of individual demand. We extend these insights by investigating the influence of AM's competitive advantage and competitive environment on welfare and identifying the thresholds where consumers benefit from AM adoption.

A substantial part of the existing literature on AM are studies in the field of engineering (Weller et al. 2015), although many of these studies investigate an economic perspective such as the impact of AM on supply chains (Delic & Eyers 2020), sustainability (Ghobadian et al. 2020), and production costs (Baumers & Holweg 2019). However, literature on AM in industrial organization is scarce and limited to just a few studies. Weller et al. (2015) analyze the effects of AM technology at the firm level and apply their findings to several economic models to examine changes in market structure. Among other things, Weller et al. (2015) extend the FM model of Eaton & Schmitt (1994) to design the cost structure of AM technology. Typically, digital technologies reduce some costs considerably, which may approach zero and open up new economic actions (Goldfarb & Tucker 2019). For the case of AM, they assume zero cost for modifying a basic product to any other product variant due to the elimination of assembly steps, fewer manual interventions, and the absence of moulds or tools. This change in the cost structure allows a firm to cover the whole market space and produce any variant for the same marginal costs. They simulate the entry of a firm adopting AM technology into Hotelling's linear city with three firms using FM technology. Based on their analysis, the authors conclude a decline in product prices as the entrant with AM lowers the upper-price barrier for the three incumbents.

More recent work by Kleer & Piller (2019) investigates the impact of competition between producers with AM technology and firms with TM technology. Their spatial model builds upon the approach of Salop (1979), considering an exogenously given number of firms that are equally distanced from each other on the circumference of a circle. Furthermore, they assume that producers with AM can manufacture any good within the attribute space in an AM facility, while firms manufacture standardized products in a centralized production factory. Their analysis provides insights about changes in consumer surplus, market structure, and competitive dynamics due to the adoption of AM. Kleer & Piller (2019) show a decline in firms' product prices. In addition, lower prices and consumers' opportunity to purchase customized products increase consumer surplus.

While this paper provides important insights about competitors reactions on AM entry, it remains unexplored how AM adoption changes market structure as such. In particular, how the number of incumbents reacts to the increased competition and the corresponding decline in product prices, which in turn affects competition. In order to understand the effect of the market dynamic on prices and welfare, the market adjustments on the supply side need to be taken into account by endogenizing the number of firms. Furthermore, it seems valuable to extend the model of Kleer & Piller (2019) to examine the welfare implications in detail and derive welfare maximizing policy measures. The aim of this paper is to fill these research gaps. In order to consider the market dynamics and the corresponding welfare implications of industrial AM, our model assumes that firms enter and leave the market until each producing firm with TM technology obtains zero profits. Moreover, our model examines the role of AM's competitive environment and cost advantage compared to TM technology on market structure and welfare.

3 Theoretical model

In the following four sections, we discuss the analysis of our game-theoretical model. In section 3, we start to lay out the market framework of our game and then describe the outcome of a market where firms only adopt TM technology. This market serves as a benchmark in order to determine the effects of AM adoption. In section 4, we derive the market equilibrium in the situation where TM firms compete with AM firms and compare the results with the outcome of our benchmark market. In section 5, we examine the consequences for welfare including consumer surplus and total surplus.

3.1 Model set-up

We consider a market with consumers and firms trading horizontally differentiated products. A unit-circumference of a circle defines the product space as in Salop (1979).

Technology In this market, there are two distinct technologies for manufacturing products. First, TM technology manufactures one specific product variant (henceforth standardized product), corresponding to a single location on the circle. Second, additive manufacturing (AM) allows to produce any product variant (henceforth customized product) and perfectly tailor products to consumers' needs.

We define two types of market structures in terms of technology adoption. In the first market structure (henceforth market structure I), all firms use the TM technology for production. In the second market structure (henceforth market structure II), both TM and AM technologies are in use assuming an exclusive adoption.

Consumer Consumers are uniformly distributed around the circle and its number is normalized to one. The location corresponds to the consumer‘s most preferred product variant. Moreover, we assume a covered market. In other words, each consumer purchases one unit of either a standardized or customized product.

When consumers decide to buy a standardized product, they incur a linear transportation cost t per unit of distance if the product's characteristics deviate from their most preferred product variant. In this case, a consumer with location x receives the following utility:

$$U_T^i = v - t|x^i - x| - p_T^i, \tag{1}$$

where v is the base utility, $|x^i - x|$ the distance between the firm's product and the consumer, and p_T^i is the price charged by firm i.

Instead, when purchasing the customized product, the consumer's utility is

$$U_A = v - \theta s - p_A. \tag{2}$$

As the product is customized, the consumer does not face any transportation cost. However, customization involves a cost, denoted as θs, which represents the time and effort costs associated with digital customization environments or the provision of potentially sensitive data. Here, $\theta > 0$ serves as a preference parameter of the consumer reflecting factors such as patience, communication skills in expressing product preferences, and the desire for data privacy. Similarly, $s > 0$ is a parameter related to the digital customization environment, indicating the difficulty for consumers to convey their preferences to the firm. Firms have the ability to influence this parameter by providing tools, such as user-friendly software for product design or scanners to facilitate the measurement of individual-specific geometries. Importantly, we assume the same costs for all consumers. The customized product price is denoted by p_A.

Firm If a firm enters the market, it can either adopt TM or AM technology. We define the group of firms with TM technology as TM sector and the group of firms with AM technology as AM sector. In the TM sector, there are N firms. We assume that TM firms are uniformly distributed around the circumference of a circle, with each firm equidistant from its neighboring competitor with TM technology at a distance of $\frac{1}{N}$. TM firms incur constant marginal costs of production of c_T and fixed entry cost of F_T.

In our base model, only one firm has the incentive to adopt AM technology. Since a customized product cannot be differentiated by definition, it represents a homogeneous product. In the light of Bertrand competition, entry of an additional firm with AM technology would lead to marginal cost pricing and, hence, in the presence of entry costs to losses for all AM firms. In an extension, we later consider the implications of additional competition in this sector. Firms incur constant marginal production costs of c_A. In order to enter the market with AM, a firm must pay a fixed cost of F_A.

While costs are identical within each sector, we allow costs to differ across technologies. In our later analysis, it will be useful to define a measure for the competitive advantage of AM, denoted by ω. Let

$$\omega = c_T - c_A - \theta s \gtreqless 0,$$

such that higher values of ω represent higher competitive advantage of the AM technology. Note that this measure comprises elements from the production side (c_A and c_T) as well as elements from the consumption side (θs). One main objective of our analysis is to investigate the impact on market outcomes as the competitive advantage of AM technology increases.

Timing We consider the following sequence of events. In the first stage, the firm with AM technology decides whether to enter the market. In the second stage, firms using TM technology make their market entry decision. In the third stage, all firms simultaneously determine their pricing strategies. Our analysis focuses on solving for subgame perfect Nash equilibria.

3.2 Benchmark market with TM firms

In this subsection, we consider market structure I. This market structure serves as a benchmark case and corresponds to the standard Salop setting (Salop 1979). In this market, all firms adopt TM technology. For convenience and for later comparisons, we briefly reproduce the main results (see, e.g. Tirole 1988).

Given the consumer utility in (1), we can derive the marginal consumer who is indifferent between any two neighbouring standardized products. Consider the standardized product from firm i whose demand is given by

$$q_T^i = \frac{1}{N} + \frac{p - p_T^i}{t},$$

where p_T^i is the price charged by firm i and p is the price charged by all other firms. Given demand q_T^i, each firm i maximizes its profits given by

$$\Pi_T^i = (p_T^i - c_T)q_T^i - F_T.$$

For a given number of TM firms N, symmetric equilibrium prices and profits are represented by

$$p = \frac{t}{N} + c_T,$$

and

$$\pi = \frac{t}{N^2} - F_T,$$

while consumers receive a surplus of

$$CS^I(N) = v - \frac{5}{4}\frac{t}{N} - c_T.$$

TM firms have an incentive to enter the market as long as non-negative profits are expected. Hence, we determine the number of TM firms via a zero-profit condition, yielding an equilibrium number of firms of

$$N^I = \sqrt{\frac{t}{F_T}}.$$

Given N^I, the resulting equilibrium price is

$$p^I = \sqrt{F_T t} + c_T,$$

and consumer surplus is

$$CS^I = v - \frac{5}{4}\sqrt{tF_T} - c_T, \tag{3}$$

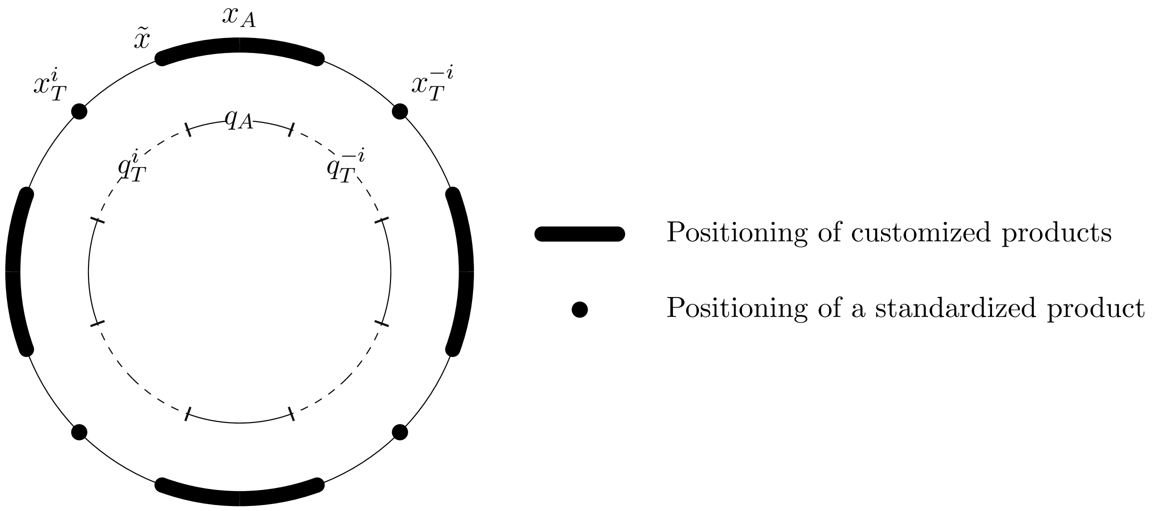
when the number of TM firms is endogenously determined. We note that consumer surplus is reduced when production, entry, and transportation costs are high.

4 Competition between AM & TM firms

In market II, both technologies coexist, leading to competition between TM firms and an AM firm. The analysis starts with the derivation of the market shares for both the TM sector and AM sector followed by the determination of equilibrium prices and the resulting equilibrium market structure.

Market share of the TM and AM sector In market II, a consumer has the option to choose between a standardized product offered by one of the TM firms or a customized product from the AM firm. Notably, the customized product ensures a constant utility for consumers, while the utility of TM firms' products depends on the consumers' locations. As illustrated in Figure 1, the customized products are strategically positioned between the locations of any two standardized products. This positioning avoids direct competition between TM firms (Balasubramanian 1998, Weller et al. 2015). In this scenario, the AM firm competes directly with all TM firms, while TM firms only engage in indirect competition among themselves. Figure 1 provides a visual representation for the case involving four TM firms and one firm utilizing AM technology. The bold lines denote the locations of customized products, and the dots indicate the positions of standardized products. Additionally, the arcs of the bold lines represent the locations where consumers are drawn to customized products, while the arcs around standardized products signify the consumers served by a TM firm.

Figure 1: Firm positioning and demand in market structure II



In order to derive the demand functions, we identify the marginal consumer located at $\tilde{x}$. In this market, the marginal consumer is defined as the consumer who is indifferent between the consumption of a standardized product and customized product:

$$\tilde{x} = \frac{p_A - p_T^i + \theta s}{t}.$$

All consumers located between x_T^i and $\tilde{x}$ opt for a standardized product. Due to symmetry in the market, firm i captures the demand of twice this distance. Consequently, the demand for firm i is expressed as

$$q_T^i = 2\frac{p_A - p_T^i + \theta s}{t},$$

such that the total demand by the TM sector is

$$Q_T = 2N\frac{p_A - p_T + \theta s}{t},$$

imposing that all TM firms charge the same price p_T in equilibrium. Hence, the AM sector faces demand of

$$q_A = 1 - 2N\frac{p_A - p_T + \theta s}{t}.$$

The demand functions show that an increase in the transportation cost decreases the market share of the TM sector (Q_T) while, ceteris paribus, an increase in the number of TM firms and the price difference between standardized and customized products increases the market share. In contrast, the impact of these variables on the market share of the AM sector (q_A) have the opposite effects.

Equilibrium prices with an exogenous number of TM firms We start our equilibrium analysis by assuming an exogenous number of TM firms. Subsequently, we will investigate how the number of TM firms changes following the entry of a firm with AM technology.

In the following analysis with an exogenous number of TM firms, we make the following parameter assumptions.

Assumption 1

$$t > \max[2N\omega, -N\omega]$$

This assumption ensures that, in equilibrium, both types of firms remain active, each serving a positive mass of consumers.

Given the market shares, the representative TM firm i aims to maximize

$$\pi_T^i = 2\left(\frac{p_A - p_T^i + \theta s}{t}\right)(p_T^i - c_T) - F_T,$$

and the AM firm maximizes

$$\pi_A = \left(1 - 2N\frac{p_A - p_T + \theta s}{t}\right)(p_A - c_A) - F_A,$$

which already takes symmetric TM prices into account. Consequently, the resulting equilibrium prices are

$$p_T = \frac{1}{3}\left(\frac{t}{2N} - \omega\right) + c_T,$$
$$p_A = \frac{1}{3}\left(\frac{t}{N} + \omega\right) + c_A.$$

As in standard models, we observe that prices are increasing in transportation costs t. This effect is more pronounced for the price of firm A. As t increases, the AM firm raises its price to a greater extent. This strategic decision is due to the fact that higher transportation costs increase the attractiveness of the customized product relative to the products of TM competitors. Additionally, our findings indicate a decline in prices with the number of TM firms. Interestingly, the AM firm is more responsive to changes in the number of rivals with TM technology leading to a stronger reaction in its pricing strategy.

Given prices, the equilibrium market share of the AM firm is

$$q_A = \frac{2}{3}\left(1 + \frac{N\omega}{t}\right),$$

and its profits are

$$\pi_A = \frac{2}{9}\frac{(t + N\omega)^2}{Nt} - F_A.$$

Differentiation of the market share and profits with respect to N yields the following result:

Lemma 1 *(i) A larger number of TM firms increases the market share of the AM firm if its competitive advantage is sufficiently strong ($\omega > 0$) and reduces it otherwise ($\omega < 0$). (ii) A larger number of TM firms reduces TM profits.*

Contrary to standard intuition, the first part of the lemma suggests an incline in the market share of the AM sector if the number of TM firms increases. This effect occurs when the AM firm faces relatively weak TM firms and offers a superior product ($\omega > 0$). However, the market share of the AM sector decreases with the number of TM firms if the production technology is inferior ($\omega < 0$).

Part (ii) of the lemma asserts that a firm with TM can never benefit in terms of higher profits from a larger number of TM firms. The negative effect of lower prices dominates the potentially positive effect of a larger market share.

Number of TM firms and prices with endogenous entry In the following, we examine the effects of AM entry when the market structure changes due to AM adoption. Therefore, we consider the scenario of free market entry for TM firms.

With free market entry, TM firms enter the market until each TM firm profits, π_T, equals fixed costs, F_T. By using this condition and solving for N, we can determine the equilibrium number of TM firms active in the market:

$$N^{II} = \frac{t}{3\sqrt{2F_T t} + 2\omega}.$$

The number of firms with TM technology depends on transportation cost and the characteristics of both technologies. An increase in transportation cost or a decrease in the competitive advantage of TM firms (ω) increases, ceteris paribus, the number of firms with TM technology. In contrast, an increase in the TM fixed cost decreases, ceteris paribus, the number of TM firms.

For later reference, we compare the entry level in this setting with the entry level in the standard Salop setting. The comparison yields:

Proposition 1 *Market structure II contains a smaller number of firms using TM technology than market structure I ($N^{II} < N^{I}$).*

The proposition shows that the number of standardized products is smaller in the presence of a firm offering a customized product. The intuition for this findings is straightforward. The entry of an AM firm increases the intensity of competition, reducing profits of TM firms. In turn, this forces some TM firms out of the market such that the overall number of firms is reduced.

We now determine prices taking into account the effects of endogenous market entry. Inserting the number of TM firms into the prices yields the following prices:

$$\begin{aligned} p_T^{II} &= \sqrt{\frac{F_T t}{2}} + c_T, \\ p_A^{II} &= \sqrt{2F_T t} + c_T - \theta s. \end{aligned}$$

In the equilibrium with free TM entry, the prices of both technologies depend on the transportation cost, fixed cost, and marginal cost of firm T, like in market II. An increase in one of these costs leads, ceteris paribus, to higher product prices. Moreover, the AM firm charges a higher price than firms with TM technology.

For our later welfare analysis, it is useful to compare the price levels across the two market structures. We observe that the prices of standardized products are always lower when the AM technology is adopted, specifically $p_T^{II} < p^I$. This aligns with intuition as TM firms face intense competition from the AM firm leading to a reduced number of TM firms and subsequently lower prices. In contrast, the price of the AM firm may be either higher or lower than prices in the market with only TM firms ($p_A^{II} \lesseqqgtr p^I$). More specifically, we find that consumers may face higher prices due to AM entry when $\theta s < (\sqrt{2} - 1)\sqrt{F_T t}$. In other words, consumer may have to pay a higher price if the customization costs are low. For low values of θs, the AM firm offers a superior product compared to TM firms, enabling it to charge high prices. In summary, these price comparisons reveal that a priori it is ambiguous whether consumers can benefit from the entry of the AM technology in terms of prices.

Equilibrium market structure Thus far, our analysis has assumed entry and production of firms with both technology types in the market. In the following, we are deriving conditions that ensure both AM and TM firms indeed have the incentive to enter the market. Thereby, we will also determine the equilibrium market structure, which is contingent on the characteristics of the production technologies.

For the existence of market structure II, two conditions must be satisfied. First, the AM firm needs to make a non-negative profit. Second, there must be at least one TM firm that finds it profitable to enter. In turn, we consider both requirements.

The firm with AM technology realizes non-negative profits, $\pi_A(N^{II}) \geq 0$, when

$$\omega \geq \frac{F_A}{2} - \sqrt{2F_T t} + \frac{1}{2}\sqrt{2F_A\sqrt{2F_T t} + F_A^2} = \omega_L$$

In words, the firm with AM technology finds it worthwhile to enter the market only if its competitive advantage, ω, is larger than the critical threshold level ω_L.

The second requirement is that TM firms find it profitable to enter the market, $N^{II} \geq 1$. At least one firm uses TM technology if

$$\omega \leq \frac{t}{2} - \frac{3}{\sqrt{2}}\sqrt{F_T t} = \omega_H.$$

That is, for TM firms to enter the market the competitive advantage of the AM technology must not be too large.

Taken together, the market structure II results only if both conditions are satisfied simultaneously. In other words, market structure II occurs for $\omega_L \leq \omega \leq \omega_H$. Therefore, a necessary condition for existence of market structure II is $\omega_H > \omega_L$:

$$t \geq F_A + \sqrt{2F_A\sqrt{2F_T t} + F_A^2} + \sqrt{2F_T t}, \tag{4}$$

which we will assume in the following. Consequently, a market where both technologies are in use can only exist when the transport cost parameter t is sufficiently large. In other words, the preference for a specific product must be sufficiently high.

Summarizing the preceding discussion, the next proposition presents the equilibrium market structure.

Proposition 2 *Suppose condition* (4) *holds. Then:*

(i) If $\omega > \omega_H$: The AM firm holds a monopoly.

(ii) If $\omega_H \geq \omega \geq \omega_L$: Mixed market with AM and TM firms.

(iii) If $\omega < \omega_L$: Only TM firms are active.

The proposition outlines the equilibrium market structure, emphasizing its dependence on the technological characteristics of both technologies. When ω takes on large values, the dominance of AM technology allows the adopting firm to monopolize the market. Conversely, for small values of ω, the inferiority of AM technology hinders its competitiveness against TM firms. In such cases, there is no AM entry, and the market is characterized by firms only offering standardized products. Finally, for intermediate values of ω, both technologies coexist in equilibrium.

5 Welfare analysis

This section presents the implications for welfare encompassing both consumer surplus and total surplus. The analysis unfolds in two steps. In the first step, we calculate consumer surplus and total surplus for market structure II and provide comparative statics. In the second step, we investigate the impact of AM entry by comparing welfare under this scenario with our benchmark market (market structure I).

5.1 Welfare in market structure II

We begin our analysis by calculating consumer surplus in market structure II. Given equilibrium entry and prices, the expression for consumer surplus is as follows:

$$CS^{II} = 2N^{II} \int_0^{\frac{1}{2}q_T(N^{II})} (v - p_T - tx)dx + Q_A(N^{II})[v - p_A - \theta s].$$

In this expression, the two terms represent the surplus from the two market sectors. The first term is the surplus from the traditional sector providing standardized products. A consumer at x earns a surplus of $v - p_T - tx$ which is integrated over all consumers buying this product type. The second term provides the surplus from the consumption of the AM product. Each consumer receives a surplus of $v - p_A - \theta s$ which is multiplied by the AM equilibrium market share.

We can rewrite consumer surplus as

$$CS^{II} = v - p_A^{II} - \theta s + \frac{N^{II} F_T}{2}. \tag{5}$$

For our later analysis, the following finding is useful.

Lemma 2 *A larger number of TM competitors increases consumer surplus.*

An increasing number of TM firms contributes to a rise in consumer surplus for two reasons. First, consumers benefit from elevated competition, resulting in lower prices for standardized products. Second, consumers also experience advantages from the reduction in total transportation costs, facilitated by a larger number of standardized products, which better aligns with their preferences.

Total surplus in market structure II is calculated as follows.

$$TS^{II} = 2N^{II} \int_0^{\frac{1}{2}q_T(N^{II})} (v - c_T - tx)dx + q_A(N^{II})[v - c_A - \theta s] - N^{II}F_T - F_A.$$

Analogously to consumer surplus, the first two terms denote total surplus generated in the two market sectors. The last two terms account for fixed costs associated with market entry. It is noteworthy that prices are mere transfers between consumers and firms and, therefore, do not exert a direct impact on total surplus.

From the calculations of the consumer surplus and total surplus, we can derive the following proposition about the comparative statics effects of AM's competitive advantage on welfare.

Proposition 3 *Suppose $\omega_H \geq \omega \geq \omega_L$ and endogenous entry of TM firms. Then, a larger competitive advantage of the AM technology (ω)*

(i) reduces consumer surplus.

(ii) increases total surplus.

The proposition states detrimental effects on consumers if factors, either by reducing the marginal cost of AM technology or by lowering the customization cost, strengthens the competitiveness of AM. This counterintuitive finding challenges standard assumptions as technology improvement typically enhances consumer surplus. Three effects emerge when AM becomes more competitive. There is a direct positive effect, resulting in lower costs or improved services that benefit consumers through reduced prices of standardized products or customized products eliminating transportation costs. Concurrently, there are two effects working in the opposite direction. An increase in ω improves the competitive standing of the AM firm regarding the TM firms allowing to raise the price of customized products. Furthermore, the expansion of AM firm's market power compels some TM firms to exit the market, resulting in higher transportation costs for some consumers due to a decline in the variety of standardized products. In this framework, the combined negative impact of increased average market prices and higher transportation costs dominates leading to detrimental consequences for consumers.

In contrast to consumer surplus, the proposition also claims a rise of total surplus if the competitive advantage of the AM technology increases. Since total surplus is unaffected by prices, only two effects need consideration. First, there is the direct effect of lower costs and an enhanced product fit. Second, it is widely acknowledged that the standard model, without AM firms, exhibits excessive market entry (Salop 1979). Therefore, a decline of TM firms contributes to a growth in total surplus. Combining these effects leads to the unambiguous conclusion that total surplus rises with improvements in AM technology.

The next finding follows directly from Proposition 3.

Corollary 1 *Suppose $\omega_H \geq \omega \geq \omega_L$. Then, consumer surplus is maximal when $\omega = \omega_L$ and total surplus is maximal when $\omega = \omega_H$.*

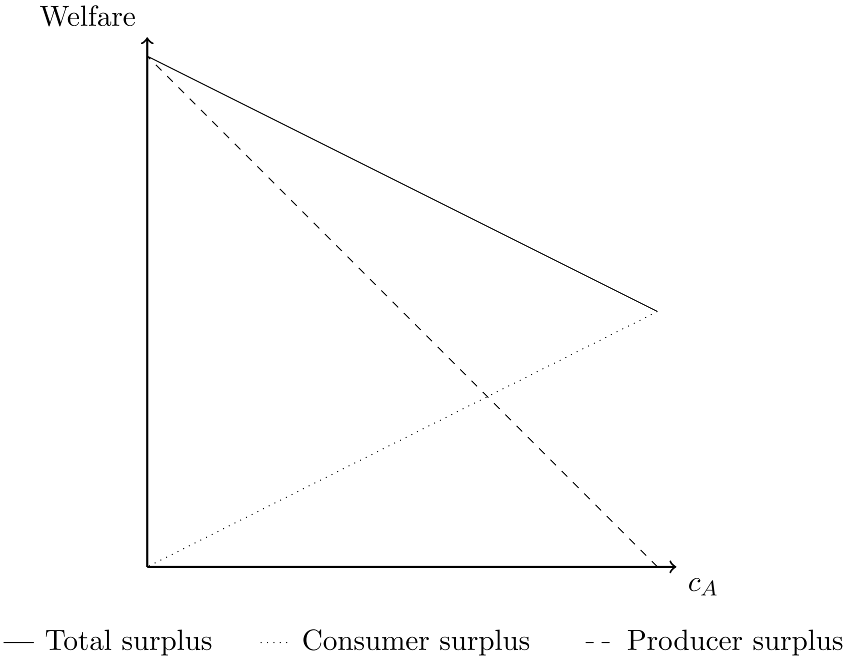
Proposition 3 and Corollary 1 yield policy implications, visually represented in Figure 2. In the presence of an equilibrium where both technologies are adopted, a divergence emerges between consumer surplus and total surplus. Total surplus is maximized when the competitive advantage of AM technology is at its peak, while consumer surplus reaches its zenith when the competitive advantage of AM technology is minimized. This holds true as long as both technologies maintain positive market shares in equilibrium.

These findings have significant policy implications, particularly concerning potential subsidies for AM technology. Subsidies, whether through reducing marginal costs of AM technology or lowering customization costs, result in an increase in total surplus. However, consumers do not benefit; instead, they are adversely affected. The surplus generated is appropriated by the AM firm, thereby raising its market power. This increased market power enables the AM firm to raise prices, potentially driving other firms out of the market and leaving consumers worse off.

5.2 Welfare implications of AM entry

The previous subsection demonstrated a decline in consumer surplus (and an increase in total surplus) with a rise in the competitive advantage of the AM technology. In the light of this finding, the question arises whether consumers benefit from the entry of AM technology. Therefore, we now compare consumer surplus and total surplus in market structure II with the outcomes of market structure I (as derived in section 3.2).

Figure 2: Welfare in market structure II



Exogenous market entry of TM firms Comparing the consumer surplus in market structure II with a given number of TM firms with the benchmark market outcome yields the following result.

Proposition 4 *(i)* $CS^{II}(N) > CS^{I}(N-1)$*. (ii)* $CS^{II}(N) > CS^{I}(N)$*.*

The proposition indicates an increase in consumer surplus for an exogenous number of TM firms caused by the adoption of AM technology. This finding comes in two versions. Part (i) says that, if we fix the total number of firms in the market, and one firm switches from TM to AM technology, then consumers benefit. Part (ii) shows that, if we fix the number of firms operating under TM technology, the entry of a new firm using the AM technology raises consumer surplus. In both cases, consumers benefit from AM entry.

Endogenous market entry of TM firms Considering endogenous entry of TM firms, we compare the consumer surplus in market structure I (3) with market structure II (5). This comparison yields:

$$\begin{aligned} & CS^{I} \lesseqqgtr CS^{II} \\ \Leftrightarrow \qquad & \omega \gtreqqless \frac{10-13\sqrt{2}}{14}\sqrt{F_T t} \end{aligned}$$

Proposition 5 *Suppose* $\omega_H \geq \omega \geq \omega_L$*. With endogenous TM entry, AM adoption* *(i) increases consumer surplus if and only if* $\omega < \frac{10-13\sqrt{2}}{14}\sqrt{F_T t}$*. Otherwise, consumer surplus remains equal or declines.*

(ii) increases total surplus.

The proposition asserts that total surplus in market structure II always surpasses total surplus in market structure I. Nevertheless, the proposition also states that the adoption of AM may not necessarily lead to an improvement in consumer surplus. To be more precise, consumer surplus increases only when the competitive advantage of AM technology is not excessively large. This insight is derived from the findings in Lemma 3 and Proposition 4, which demonstrate that consumer surplus attains its maximum when the competitive advantage (and market power) of the AM firm is at its lowest possible level.

Examining the proposition from another angle involves considering its implications for AM profits. In the traditional sector, where firms earn zero profits, the disparity between total surplus and consumer surplus represents AM profits. Consequently, when the competitive advantage of AM technology is substantial, the AM firm not only gains access to the additional total surplus but also manages to appropriate a larger portion of consumer surplus. This dynamic results in diminished consumer surplus, despite an overall increase in total surplus.

We observe that this finding stands in contrast to the welfare analysis conducted under the assumption of a exogenous number of TM firms. In Proposition 4, we demonstrated that consumer surplus increases with AM entry, assuming a constant number of TM firms. In contrast, this analysis reveals that this outcome can be reversed when considering the possibility of TM exit induced by AM entry, coupled with the potential for the AM firm to gain significant market power at the expense of consumers.

Previously, we stated that subsidizing production costs could negatively impact consumers. This conclusion was drawn under the assumption of viable AM entry, leading to competition between firms employing AM and TM technologies. However, we now assert that there exists a rationale for subsidies aimed at increasing consumer surplus despite this initial argument.

The subsequent proposition asserts that subsidies targeting fixed costs have the potential to enhance consumer surplus, particularly when they facilitate the entry of AM.

Proposition 6 *Suppose that* $\omega < \omega_L$ *such that no AM entry occurs absent AM subsidisation. Let* $\bar{S}$ *be implicitly given by*

$$\frac{F_A - \bar{S}}{2} - \sqrt{2F_T t} + \frac{1}{2}\sqrt{2(F_A - \bar{S})\sqrt{2F_T t} + (F_A - \bar{S})^2} = \omega.$$

Then, if $\frac{10-13\sqrt{2}}{14}\sqrt{F_T t} > \omega > -\sqrt{2F_T t}$ *a fixed-cost subsidy* $S > \bar{S}$ *increases consumer surplus.*

Consider a situation where fixed costs are prohibitively high, preventing profitable entry for the AM firm without policy interventions ($\omega < \omega_L$). However, the competitiveness of the AM technology is such that the firm can attain a positive market share once entry is feasible ($\omega > -\sqrt{2F_T t}$). The proposition establishes that a government can increase consumer surplus by subsidizing fixed costs, given that ω is not excessively large, where $\frac{10-13\sqrt{2}}{14}\sqrt{F_T t} > \omega$ (derived from Proposition 5).

6 The effect of intensified competition for AM firm

In our baseline model, we considered the entry of one AM firm. Our results indicate a substantial attainment of market power by this firm, especially when its competitive advantage is significantly high. The resulting profits from AM technology might attract more firms to adopt AM. Therefore, it is crucial to investigate the implications if the AM firm encounters intensified competition, such as from additional competitors with the same technology.

In this section, we discuss the consequences of intensified competition for the AM firm on consumer surplus and its subsequent policy implications. To facilitate a manageable analysis, we employ a stylized, reduced-form framework. Here, we assume that a portion of the AM firm's customers have the option to switch to an alternative product choice.

Formally, we introduce a second stage into the consumer decision process. In this new stage, a share of the AM firm's consumers $\lambda \in (0, 1)$ has the option to switch to an outside alternative. However, the AM firm has the possibility to retain its consumers by offering a discount of $\delta > 0$. The parameter δ is interpretable as the competitive pressure from other customized products, where higher values signify more intense competition faced by the AM firm. Alternatively, the intensity of competition can be measured by the share of contested consumers (λ).

Given this modification, the AM firm's profit function becomes

$$\pi_A = \left(1 - 2N\frac{p_A - p_T + \theta s}{t}\right)[\lambda(p_A - \delta) + (1-\lambda)p_A - c_A] - F_A,$$

while the profit function of any TM firm as well as all other elements of the model are unchanged.[4]

---

[4] All derivations are relegated to the Appendix.

Following the same steps as in our baseline model, we proceed to calculate equilibrium prices and derive equilibrium entry levels. An immediate finding is that AM profits experience a reduction in the face of a more competitive environment, indicated by higher values of δ and λ. The following proposition unveils the resulting equilibrium market structure.

Proposition 7 *Suppose the AM firm needs to offer a discount of $\delta > 0$ to a share $\lambda > 0$ of its customers. Then, the following market structure emerges.*

(i) If $\omega > \omega_H(\delta\lambda)$: The AM firm holds a monopoly.

(ii) If $\omega_H(\delta\lambda) \geq \omega \geq \omega_L(\delta\lambda)$: Mixed market with AM and TM firms.

(iii) If $\omega < \omega_L(\delta\lambda)$: Only TM firms are active.

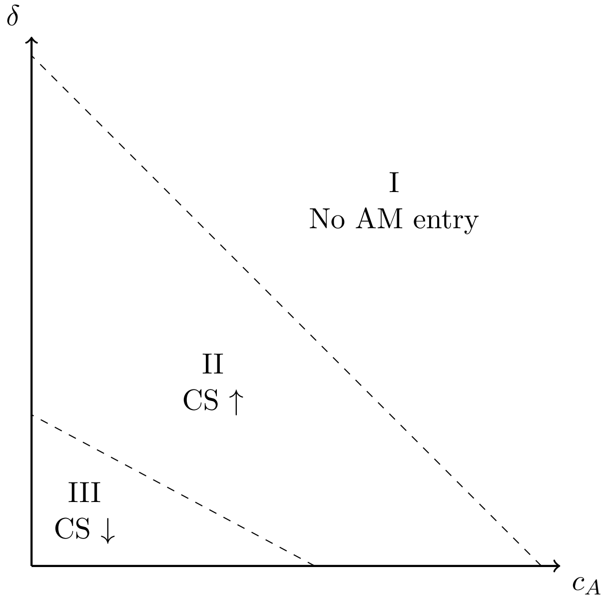
The critical levels $\omega_L(\delta\lambda)$ and $\omega_H(\delta\lambda)$ are increasing in δ and λ.

The market configuration follows a similar structure as in the baseline model. For intermediate levels of ω, both types of firms are active in the market. For high or low values of ω, only one type of firm stays in the market. What distinguishes this model is that the critical values, $\omega_H(\delta\lambda)$ and $\omega_L(\delta\lambda)$, are now contingent on the competitive pressure exerted by an additional potential AM firm, as parameterized by δ. Notably, both critical levels exhibit an increase with higher values of δ. This trend aligns with intuition. As increased δ values intensify competitive pressure on the AM firm, its profits diminish. This reduces the likelihood of market monopolization by the AM firm, thereby expanding the parameter values within which TM firms can survive. Moreover, as ω_L is increasing in δ and λ, AM entry is only viable for a smaller parameter range than in the baseline model.

Besides its impact on equilibrium entry levels, intensified competitive pressure on the AM firm has significant implication for the welfare outcomes, particularly regarding consumer surplus. There are two effects to consider. The first effect demonstrates that consumer surplus increases with the intensity of AM competition. This observation aligns with intuitive reasoning, as intensified competition often leads to lower prices for AM products, thus benefiting consumers. However, there exists a second effect. With the viability of AM entry dependent on more restrictive conditions, there is a higher likelihood that such entry may not occur, consequently reducing the parameter range wherein consumers can benefit.

Figure 3 summarizes the essence of our discussion by considering whether consumers would benefit by the entry of AM firms compared to the market outcome with only TM

Figure 3: Impact of AM's competitive pressure and marginal cost on consumer surplus



firms. The figure distinguishes three distinct areas: In area I, consumers would benefit from entry, but entry does not take place. In area II, consumers benefit from AM entry and it successfully take place. Finally, in area III, entry takes place but is detrimental for consumers. Consistent with above discussion, the figure illustrates the interplay of positive and negative effects associated with promoting competition. On the one hand, an increase in δ diminishes the extent of area III, indicating a reduced likelihood of consumers being adversely affected by AM entry. On the other hand, as the conditions for AM entry become more restrictive, area I expands with higher values of δ.

Several new policy implications emerge from our findings. First, fostering competition expands the potential for consumer-surplus-enhancing adoption of AM technologies. In fact, if competition reaches a sufficiently intense level, consumers will consistently benefit from the entry of AM firms. Conversely, regulators must be aware about the fact that the adoption of the new technology becomes more costly when competition is promoted to the extent that entry might not occur. Therefore, promoting competition may require complementary measures such as increased subsidies to ensure the successful adoption of the new technology.

7 Managerial and policy implications

This study demonstrates how the adoption of AM affects market competition between firms producing standardized products with TM technology and firms producing customized products with AM technology. Our model results have useful implications for managerial decision-making regarding technology adoption, pricing strategies, product positioning, and for policymakers aiming to implement welfare maximizing policies in the manufacturing industry.

7.1 Managerial recommendations

Managers in the manufacturing sector contemplating AM adoption should assess various market characteristics, e.g. consumer preferences for individualized products, the competition with other firms with AM, and consumer ease of customization. In conformity with expectations, AM unleashes its highest potential in markets where consumers have a high need for customized products and a low level of competition with other customized products. Moreover, consumers effort to convey product preferences affect the demand for customized products and should therefore be taken into account. This exertion could include the obtainment of a digital imprint, e.g. the head shape for a customized helmet, or time to explain the product specifications to the manufacturer. Thereby, privacy concerns may play an important role. Another dimension for the adoption decision is the cost structure of AM. The marginal cost difference between the production with AM and TM technology determines the profitability of AM. Among other factors, the marginal costs includes material cost, printing speed, development of the CAD-models. While marginal costs of AM not only influences the profitability of AM but also the competition with traditional manufacturers, AM's fixed costs only affects the moment when it becomes profitable for companies to adopt AM.

The adoption of AM and the supply of customized products influence companies' pricing strategies for both AM adopters and traditional manufacturers. While companies with AM can consider to impose a price premium for customized products, they should also account for consumers' associated customization efforts and the competition from other customized products. In response to fiercer price competition, traditional manufacturers should strategically reduce product prices to maintain competitiveness. Yet, the magnitude of the decline depends on the competition between firms with AM technology. The higher the competition intensity, the lower the required price reduction for standardized products.

Due to high prices for customized products, companies with AM should target consumers who prefer product variants with strong diverging specifications compared to standardized products. Therefore, the direct competitors for traditional manufacturers are shifting from other manufacturers with standardized products towards manufacturers with customized products. As a consequence, the emphasis on strategic product positioning for standardized products diminishes in significance.

7.2 Policy recommendations

Policymakers should distinguish between static effects (comparative statics in market structure II) and dynamic effects (adoption of AM technology) in order to identify optimal policy instruments. Table 1 provides an overview of the impact of different policy programs on welfare.

Table 1: Policy programs and welfare implications

		Static effects		Dynamic effects	
Policy	Program	CS	TS	CS	TS
Subsidies	↓ Marginal cost	−	+	+	+
	↓ Fixed cost	0	+	+	+
	↓ Customization cost	−	+	+	+
Regulations	↑ Competitive environment	+	−	−	−

Notes: This table reports the effect of policy programs on consumer surplus (CS) and total surplus (TS) distinguished by static effects and dynamic effects. The arrows (↓ and ↑) indicate the direction of cost changes caused by a policy program. ↓ denotes a cost decline and ↑ denotes a cost incline. The symbols +, −, and 0 indicate welfare changes. + denotes a positive effect, − denotes a negative effect, and 0 denotes no effect.

Considering dynamic effects, policymaker should facilitate the adoption of AM in order to enhance total surplus. In markets where consumers have a high need for customized products and the production fixed costs of TM technologies are relatively expensive, AM adoption additionally increases consumers surplus. As long as AM's cost efficiency and the market power is not too high, consumers will benefit from the offer of customized products. In order to facilitate an earlier adoption of AM, policymakers should grant market leeway or market power to firms involved in AM. If AM's cost efficiency is rather low and competition high, there is the risk of AM rejection for the production of customized products reducing the likelihood of AM adoption. The subsidization of any AM related costs supports the adoption of AM and therefore consumer surplus and total surplus.

From a static perspective, a growing competitive cost advantage compared to TM technologies will enlarge the demand for customized products and cease the supply of some standardized products. Consumers' opportunity to consume expensive customized products does not compensate the decline of low-priced standardized goods and are harmful for consumers. Therefore, a decline in AM's marginal costs or consumers' customization costs will reduce consumer surplus. In order to counteract this effect and strengthen companies with standardized products, policymaker could foster the competition between AM companies. A change in AM's fixed cost does not affect consumer surplus per se. Conversely to consumer surplus, total surplus benefits from lower marginal cost and customization cost due to the fact that a more superior AM technology restricts excessive entry (compare with Salop (1979)). Hence, a more competitive environment for companies with customized product would reduce total surplus. A subsidization in AM's fixed cost will reduce the aggregate sum of all fixed costs and thus increase total surplus.

Table 1 emphasizes heterogeneous outcomes of the discussed policy programs for consumer surplus considering static and dynamic effects. Only the subsidization of AM's fixed cost depicts the potential of a Pareto improvement. In terms of total surplus, a reduction of AM specific costs (marginal cost, fixed cost, and customization cost) and less competition for companies with AM have a positive impact.

8 Future research

There remain open questions for future research. So far, the competition intensity and market concentration between firms with AM technology is unclear. On the one hand relatively low fixed costs could incentivizes market entry and thus higher level of competition. On the other hand, potential scale effects from the usage and development of the digital input designs could increase the market power for some firms. Especially, the consequences of generative artificial intelligence, such as generative design software, on market dynamics would be interesting to explore since it might substantially affect the production with AM in the future.

In our model, we consider AM's feature to flexible produce any product variant and assume no quality differences between standardized and customized products. However, a central advantage of AM is to add product functionalities and manufacture products that cannot be produced with TM technologies, e.g. complex geometries. Extending our analysis by a quality dimension would be an interesting avenue for future studies and would change the circumstance that only one company adopts AM.

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A Appendix

A.1 Derivations section 6

Here, we provide the detailed derivations of the extended model presented in Section 6. We follow the same steps as in the base model.

Maximizing the profit functions stated in the main text, we can derive equilibrium prices for a given number of TM firms:

$$\begin{aligned} p_T &= \frac{1}{3}\left(\frac{t}{2N} - \omega + \delta\lambda\right) + c_T, \\ p_A &= \frac{1}{3}\left(\frac{t}{N} + \omega + 2\delta\lambda\right) + c_A. \end{aligned}$$

As consumers of the AM firm receive a discount, the effective price is:

$$p_A^{\text{eff}} = \frac{1}{3}\left(\frac{t}{N} + \omega - \delta\lambda\right) + c_A.$$

Customers of the AM firm are benefiting from intensified AM competition via lower prices.

Given these prices, the profit of the AM firm is:

$$\pi_A = \frac{2}{9}\frac{(t + N(\omega - \delta\lambda))^2}{Nt} - F_A,$$

which is decreasing in the extent of AM competition.

Inserting the equilibrium prices in the TM profit function, we can derive the number of TM firms:

$$N^{II} = \frac{t}{3\sqrt{2F_T t} + 2(\omega - \delta\lambda)}.$$

The number of TM firms increases with δ and λ. Increased pressure on the firm with AM places TM firms in an advantageous position enabling them to achieve higher prices and profits. Consequently, a larger number of TM firms enters the market.

Equilibrium prices are

$$p_T = \sqrt{\frac{F_T t}{2}} + c_t$$

$$p_A^{\text{eff}} = \sqrt{2F_T t} + c_T - \theta s - \lambda\delta$$

To derive Proposition 7 from the main text, note that given N^{II}, the AM firm derives non-negative profits when

$$\omega \geq \frac{F_A}{2} - \sqrt{2F_T t} + \delta\lambda + \frac{1}{2}\sqrt{2F_A\sqrt{2F_T t} + F_A^2} = \omega_L(\delta\lambda)$$

Entry by at least one TM firm occurs when

$$\omega \leq \frac{t}{2} - \frac{3}{\sqrt{2}}\sqrt{F_T t} + \delta\lambda = \omega_H(\delta\lambda).$$

Together, these two critical threshold levels imply the equilibrium market structure. Hence, a market structure with both AM and TM firms occurs only if $\omega_L \leq \omega \leq \omega_H$ as detailed in Proposition 7.

Given equilibrium entry, we can derive consumer surplus

$$CS^{II} = v - p_A^{II} - \delta\lambda - \theta s + N^{II}\left(\frac{F_T}{2} - \delta\lambda\sqrt{\frac{F_T}{t}}\right).$$

Then, the comparison with consumer surplus in market I yields:

$$\begin{aligned} & CS^I \underset{>}{\overset{\leq}{=}} CS^{II} \\ \Leftrightarrow \qquad & \omega \underset{<}{\overset{\geq}{=}} \frac{2(5 - 10\sqrt{2} + \sqrt{2t})\sqrt{tF_T}\lambda\delta + 8(\lambda\delta)^2 + (22 - 15\sqrt{2})tF_t}{(10 - 8\sqrt{2})\sqrt{tF_T} + 8\lambda\delta} \end{aligned}$$

As in the main model, AM entry only makes consumers better off if the competitive advantage of the AM technology is sufficiently small. However, this critical level of ω is decreasing in the extent of AM competition, as measured by $\lambda\delta$. Therefore, the parameter space where consumer surplus is increasing becomes larger as AM competition intensifies.

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Wirtschaftsforschung GmbH Mannheim
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Economic Research

L 7,1 · 68161 Mannheim · Germany
Phone +49 621 1235-01
info@zew.de · zew.de