TUM School of Governance TUM School of Management

Munich Papers in Political Economy

Working Paper No. 07/2021

Digitalisation of Production: Industrial Additive Manufacturing and its Implications for Competition and Social Welfare

Julian Schwierzy

November 2021

Digitalisation of Production: Industrial Additive Manufacturing and its Implications for Competition and Social Welfare

Julian Schwierzy *

Abstract

The production flexibility of digital factories has the potential to revolutionise traditional manufacturing (TM) and thereby unlock a paradigm shift in production. In particular, the role of additive manufacturing (AM) technologies is gaining increased attention. Most experts consider AM as a complement to traditional manufacturing technologies. In this paper, I examine how the adoption of AM changes competition and how the coexistence with TM affects social welfare in the long-run. The results of my game-theoretical model indicate a decline in the number of companies with TM and an increase in market concentration. I show that the effect of AM adoption on prices and welfare depends on the cost structure of AM technologies. Unless the cost of AM is below a certain cut-off, its adoption is associated with a rise in prices and a decline in social welfare. The coexistence of both technologies in the same product market is therefore not necessarily beneficial for society. Based on these findings, I discuss policy implications for the stimulation of the digital transformation in the manufacturing industry. I argue that marginal cost reducing policy measures lead to a higher welfare effect than fixed cost reducing programmes.

Keywords: Digital factories, Technology adoption, Market structure, Social welfare, Product differentiation, Digitalisation, Industrial Additive Manufacturing

JEL codes: L11,L22,L23,O33

*Julian Schwierzy is affiliated to the Technical University of Munich. Correspondence address: Technical University of Munich, TUM School of Management, Dept. of Economics & Policy, Arcisstraße 21, 80333 Munich, Germany. E-mail address: julian.schwierzy@tum.de

1 Introduction

The adoption of new technologies is an important driver for technological change and economic development (Romer 1990). Digitalisation, i.e. the adoption of digital technologies, affects globalisation and competition within and across industries. In the last years, the manufacturing industry has started to introduce various digital technologies such as Artificial Intelligence, Internet of Things, and Additive Manufacturing (AM) to digitalise the production process. Among other things, these technologies empower factories to synergise between their manufacturing systems and products, which opens up new strategic options for firms and in turn affects competition (Gilchrist 2016). It is therefore not surprising that the digital revolution in the manufacturing industry is of high interest for economists, technology managers, and policy makers. Recent literature discusses how the digitalisation of factories influences industrial performance (Dalenogare et al. 2018) and sustainability (Bai et al. 2020). Potential gains also arise from the adoption of flexible manufacturing lines enabling the production of various goods (Wang et al. 2016, Frank et al. 2019). While production lines of traditional factories restrict the product variety to a few standardised products, factories with digital technologies (hereinafter digital factories) unlock the potential to customise products.
Digital technologies of AM are deemed to be one of the core manufacturing technologies to implement a flexible production in factories (Frank et al. 2019, Haleem & Javaid 2019). A shift from traditional manufacturing technologies towards AM technologies can be seen exemplary for the flexibilisation of production in the digital revolution. AM, often referred to as 3D printing, describes a group of production technologies employing a digital design data to create a physical product in a layer-upon-layer process (Gebhardt & Hötter 2016). Conversely to traditional manufacturing technologies, AM technologies 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 the product variety without significantly compromising cost efficiency (Weller et al. 2015). Furthermore, the reduction of flexibility costs allows firms to realise economies of scope (Baumers & Holweg 2019), which may cause a paradigm shift in firms' strategic positioning. Yet, the long-term effects of a strategic change in firms' product variety on the market structure and social welfare are largely unknown.

The purpose of this paper is, therefore, to shed light on the question how digitalisation with respect to the implementation of new flexible manufacturing technologies affects the competition in markets for consumer goods. In particular, I investigate how the adoption of industrial AM influences market structure and social welfare in the long-run. By analysing market structure, I focus on the number of firms in the market and their pricing strategies. I examine a spatial model using a game-theoretical approach. This model describes competition between traditional factories with TM technologies and digital factories with AM technologies in markets for differentiated products. Advancing current literature in the field of AM, e.g. see Kleer & Piller (2019), I show that in markets where both traditional manufacturing and AM technologies are employed for production, the adoption of AM leads to a decline in social welfare. This is due to the fact that the rise of average product prices is not fully compensated by the higher degree of customised products. Essentially, I show an increase in market concentration in response to AM adoption. This implies a rise in average product prices and a decline in social welfare unless the cost of AM are below a certain cut-off. The cost of AM will solely fall under this threshold in markets where AM is the only production technology.

The analysis and findings of this paper are important for at least two reasons: First, AM plays an increasingly important role in firm's serial production. Therefore, changes in competition and market structure from the flexibilisation of production may become more prevalent. Recent studies show a steady rise in the number of industrial AM adopters over the last years. According to a survey by Ernst & Young based on 900 manufacturing companies from North America, Europe, and Asia, the percentage of firms that apply AM increased from 24% in 2016 to 65% in 2019 [1] (Karevska et al. 2019). Furthermore, it is expected that a substantial number of firms will use AM for serial production and manufacturing end products in the next years (Jiang et al. 2017, Pérez-Pérez et al. 2021). The global AM market, which comprises revenues from AM systems, materials, software, and services, has tremendously grown at a compound annual growth rate of roughly 25% since 2014. While the market size enclosed $4 billion USD in 2014, the market size resulted in an overall value of $9.3 billion USD in 2018, and is predicted to reach approximately $35 billion USD in 2024 (Roberts & Varotsis 2020).

Second, governments actively promote digitalisation. In several countries, funding programmes support the adoption of digital technologies. In the United States, the Small Business Innovation Research (SBIR) programmes incentivises small companies to engage in research and develeopment (R&D) projects with the aim to develop digital technologies [2], in Germany, the Federal Ministry for Economic Affairs and Energy established a programme called "Digital Jetzt" to facilitate the digitalisation for small and medium-sized enterprises [3], in Austria, the promotional bank of the Austrian federal government (aws) provides boni for investments in digitalisation [4]. Most of these programmes aim at encouraging the adoption of digital technologies by funding and acquisition. Yet, my

[1]The data reflects the perspective from 900 executives in different-sized companies from Austria, Belgium, Canada, China, France, Germany, Italy, Japan, South Korea, Spain Switzerland, United Kingdom and United States. These companies are part of nine industries: Aerospace, Automotive, Chemicals, Construction, Consumer Packaged Goods, Electronics, Industrial Products, Life Sciences, Logistics and Transportation.

[2]See e.g. https://www.sbir.gov/node/1836087 or https://www.sbir.gov/node/801349

[3]See https://www.bmwi.de/Redaktion/DE/Dossier/digital-jetzt.html

[4]See https://www.aws.at/corona-hilfen-des-bundes/aws-investitionspraemie/

model results suggests that fixed-cost-reducing funding programmes lead to lower expected welfare outcomes than marginal-cost-reducing funding programmes.
The remainder of this paper is organised as follows. Section 2 provides an overview of relevant literature. Section 3 presents and analyses the theoretical model, and chapter 4 discusses the results. Finally, the paper concludes with a summary, model limitations, and policy recommendations.

2 Theoretical Background

This paper builds on research in the domain of industrial and production economics and draws from research on spatial product differentiation, flexible manufacturing, and additive manufacturing. A brief discussion of insights from these research fields provides an overview of relevant literature and illustrates the research gap which I am addressing in this paper. The main foundation for the model presented in section 3 is the work of Weller et al. (2015) and Kleer & Piller (2019).

2.1 Spatial Product Differentiation

Research on product differentiation with spatial models traces back to the groundwork of Hotelling (1929) and was extended by other work (Salop 1979, Eaton & Schmitt 1994, Kleer & Piller 2019). Spatial models conceptualise the market as a space where each point defines a possible product variant. The most common space types are the linear street (Hotelling 1929) and the circumference of a circle (Salop 1979). In the market design, the underlying space describes the locations of consumers' preferences and firms' product variants. Typically, it is assumed that each consumer has a preferred product variant within the space. If the consumed product deviates from the favourite variant, the consumer has to incur some form of transportation cost. Hence, consumers perceive the product variants as close but imperfect substitutes (Belleflamme & Peitz 2015). Transportation costs can be interpreted as the cost that results from the discrepancy between a consumers' most preferred and consumed product or as travel costs of a geographical distance. As a consequence of various consumer preferences, the product variant of a firm competes with the immediately adjacent product variants of its competitors. Differentiated products provides, therefore, a certain level of market power if no other firm manufactures the same variant. This competition leads to a market structure known as monopolistic competition (Chamberlin 1949). Product differentiation can be divided into a vertical and horizontal dimension (Belleflamme & Peitz 2015). A product is horizontally differentiated if a change in the product characteristic affects the utility of at least two consumers in opposite ways, e.g. a large versus a small bike helmet size. Conversely, a product is vertically differentiated if a change in the product characteristic affects the

utility of all consumers in the same way, e.g. a more fuel-saving versus a less fuel-saving aeroplane.
Several studies examined the competition and social welfare consequences of product differentiation in linear street models (Lancaster 1975, Dixit & Stiglitz 1977). The analysis of linear street models is subject to asymmetries at the edges of the street and does not allow the endogenisation of the number of firms in the market. In order to overcome this limitation, Salop (1979) investigated the structure of a circular market. He assumes that each firm produces only one product variant and must pay a fixed cost in order to enter the market. The assumption of one product variant per firm is of course a simplifying assumption, but not unplausible for traditional manufacturing and inflexible production lines, often using dedicated manufacturing technologies (DMT). Salop's welfare analysis shows that the number of firms transcends the social optimum in the long-run equilibrium if firms have free market entry and exit. This result implies an excessive product variety in the market from a social planner's point of view.

2.2 Flexible Manufacturing

In the late twentieth century, the rise of information technology (IT) has opened up new opportunities for the manufacturing industry with respect to its flexibility. Firms started to incrementally replace DMT with flexible manufacturing technologies (FMT) (Milgrom & Roberts 1990). In contrast to DMT and its focus on producing a single product variant in large quantities, FMT enables the production of several product variants in small quantities (Milgrom & Roberts 1990, Eaton & Schmitt 1994). Flexibility in manufacturing indicates the ability to realign production resources to efficiently manufacture various product variants (Sethi & Sethi 1990). Eaton & Schmitt (1994) incorporate flexbile manufacturing in a spatial model by assuming that a firm with FMT develops the capability to produce a basic product located at one point in the attribute space. Firms can alter this basic product to manufacture any other product variant. Yet, the machine's adjustment to produce a different variant causes supplementary costs. Thus, firms with FMT can produce various product variants, but have to incur higher production costs for every additional variant.
Several studies discuss firms' incentives to adopt flexible manufacturing technologies. Röller & Tombak (1990) consider the choice between FMT and DMT by investigating a two-stage Cournot game. They assume that both technologies entail equal marginal costs, but the fixed costs for FMT are higher than for DMT. In addition, the dedicated firms operate only in one market, whereas the flexible firms can simultaneously operate in multiple markets. They show how the choice of technology differs under varying market structures and conclude that firms are more likely to adopt FMT in larger markets, in markets with a high degree of product differentiation, and few competitors. Chang

(1993) argues that the adoption of FMT 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 employ FMT if the variability in consumer preferences is high. Norman & Thisse (1999) analyse market structure implications from FMT adoption in a spatial model. They show that the production flexibility of FMT 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 FMT are not committed to a set of prices and can more easily change their price strategy to deter potential entrants. Norman & Thisse (1999) further show that the adoption of flexible manufacturing technologies leads to a tougher price regime. Nevertheless, consumers may not benefit from the new price regime since it deters entry and will not necessarily lead to lower prices. In general, previous research shows that flexible manufacturing facilitates market concentration and does not necessarily benefit consumers (Chang 1993, Eaton & Schmitt 1994, Norman & Thisse 1999).

2.3 Additive Manufacturing

The impact of digital technology on economic activity is attracting increasing attention in the context of flexible manufacturing (Dewan et al. 2003, Bernhardt et al. 2007, Weller et al. 2015, Kleer & Piller 2019). Most AM processes are categorised as digital technologies and pertain to flexible manufacturing technologies (Eyers et al. 2018). 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 economics is scarce and limited to just a few studies.
Weller et al. (2015) analyse 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 FMT model of Eaton & Schmitt (1994) to design the cost structure of firms with 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 the 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 employing AM technology into Hotelling's linear city (Hotelling 1929) with three firms using FMT. 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 a spatial competition between producers with AM technologies and firms with TM technologies. Their spatial model builds upon the approach of Salop (1979), considering a 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 standardised goods in a centralised production factory. Their analysis provides insights about changes in consumer welfare, 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 buy individualised goods increase consumer surplus.

While this paper provides important insights, it remains unexplored how AM adoption changes market structure as such. In particular, how the number of firms reacts to the decline in product prices, which in turn affects competition. In order to understand long-run prices and welfare implications, the market adjustments on the supply side need to be taken into account by endogenising the number of firms. Furthermore, it seems valuable to extent the model of Kleer & Piller (2019) to examine total social welfare and whether the product variety is socially optimal in markets with AM. The aim of this paper is to fill these research gaps. In order to consider the long-run market impact and the corresponding welfare implications of industrial AM, my model makes two central assumptions that extent the work by Kleer & Piller (2019). First, firms enter and leave the market until each producing firm obtains zero profits. Considering market entry and exit is important to analyse changes in the long-run market structure. Second, the price of a manufacturer with AM is mainly driven by the pricing strategy of other firms with AM. The flexible production of AM eliminates the advantages of differentiated products leading to an intense price competition among firms with AM technology. Conversely, firms with dedicated technologies might still benefit from their specialised product variants and a more favourable cost structure and therefore do not pose a high risk of intense price competition.

3 Theoretical Model

The purpose of the spatial model developed in this section is to provide a framework for the analysis of markets with heterogeneous products. In this model, I assume a simultaneous decision of firms about entry and price. Firms decide whether to enter the market with one of the available technologies or not. A firm will only enter the market as long as it is possible to obtain non-negative profits in the long-run. This assumption allows to endogenise the number of firms and to investigate changes in the long-run market structure. Moreover, the technology choice is irreversible in the short-run as the adoption of another technology requires time. Thus, entry costs are considered as fixed in the short-run. As the locations of the product variants are fixed, the price competition depends on the degree of differentiation between products. Therefore, firms consider strategic effects for the price competition already while positioning themselves in the market.

3.1 Model set-up

Assume a market with L consumers and K firms trading horizontally differentiated products. A unit-circumference of a circle (Salop 1979) defines the product space, where x_l and x_k denote the locations of the preferred product variation of consumer $l \in L$ and the offered product variations of firm $k \in K$, respectively. Consumers are uniformly distributed around the circle and the market size L is normalised to one representing a unit mass of consumers. On the demand side, each consumer buys up to one product and obtains a gross utility v for its consumption. If the product's characteristic (x_k) does not match with the preferred product (x_l), consumers have to incur a linear transportation cost t per distance unit. However, a consumer only buys a product if the resulting utility is non-negative. On the supply side, firms manufacture their products for marginal cost c_k and sell their products for the price p_k. Despite having complete information on consumers' product preferences, each firm follows an uniform pricing strategy or, in other words, does not discriminate on prices. Furthermore, each firm must pay a fixed cost F_k to enter the market.

In this market, firms adopt either traditional manufacturing (TM) technologies to operate in traditional factories or additive manufacturing (AM) technologies to produce goods in digital factories. Firm $i \in N$ produces in a traditional factory and firm $j \in M$ manufactures in a digital factory, with $i, j \subseteq k$ and $N, M \subseteq K$. The group of firms with TM technology is called traditional sector, and the group of firms with AM technology is referred to as digital sector. Within each sector, all firms have a symmetric cost structure and thus charge the same prices. The technology choice determines a firm's cost structure and the possible number of product variants. While a digital factory can produce every variation on the product space for constant marginal cost, a traditional factory produces exactly one fixed product variation and chooses a location with maximal product differentiation to neighbouring traditional factories leading to a distance of $\frac{1}{N}$.

3.2 Market Structure

Considering an exclusive technology adoption, three potential scenarios can occur. First scenario, a market where all firms use TM technology (hereinafter market I). Second scenario, a market with both TM and AM technology in use (hereinafter market II). Third scenario, a market where all firms employ AM technology (hereinafter market

III). These scenarios can be viewed as different diffusion stages of the AM technology. The following sections analyse the market structure in market *I*, *II*, and *III* comprising the price equilibrium and number of firms in the long-run. For a better comprehensibility and legibility of the model analysis, market *II* is discussed after market *III*.

3.2.1 Market *I*

In market *I*, all firms invest in TM technologies and produce their goods in traditional factories. This represents a market in the pre-digital age and serves as a benchmark to examine the impact of digitalisation. The analysis of market *I* follows the approach of Salop (1979) and reproduces the same results. Each firm $i \in N$ maximises its profits (Π_k) given a standard profit function:

$$\Pi_k = (p_k - c_k)q_k - F_k \tag{1}$$

The price influences the consumer's utility and therefore the product choice. Due to a utility maximisation, consumer l chooses the product which yields the highest utility (U_l) based on the following utility function:

$$U_l = v - p_i - t|x_i - x_l|$$

A consumer's utility depends on the reservation price, product price, and transportation cost. Therefore, a firm's product location and price affect the demand for the product of firm i and in turn the production quantity (q_i). A firm competes with all neighbouring firms for consumers' demand and chooses a location for its product variant that is maximally different from the product positions of its competitors. The concept of the marginal consumer enables to identify the total amount of consumers who buy the product of firm i. Under the assumption of a symmetric cost structure and correspondingly equal prices, the analysis with the marginal consumer results in an equal split of the market demand between all firms. With the market demand for firm i, the equilibrium price and the number of firms can be identified. The symmetric zero profit equilibrium is equivalent to the result of Salop (1979).

$$p_I = \sqrt{F_i t} + c_i \tag{2}$$

$$N_I = \sqrt{\frac{t}{F_i}} \tag{3}$$

The results of the market equilibrium show that the product price and number of firms in the long-run depend on the transportation cost and firms' cost structure including the fixed and marginal cost.

3.2.2 Market *III*

In market *III*, all firms invest in AM technologies. Conversely to traditional factories, whose product location is fixed at one specific position, a firm with a digital factory can operate around the entire circle. All firms with a digital factories are competing with each other for every considerable product variant. Thus, AM firms extent the product variety until all consumers receive their preferred product variants, as otherwise competitors could manufacture the missing variants and gain a competitive advantage. Due to the flexibility to create every product variant for constant marginal cost, AM firms try to undercut their prices for every product variant leading to fierce price competition. Thus, the price cutting behaviour would reduce the product prices until every AM firm charges a price equal to its average cost.

Charging a price higher than the average cost enables competitors to undercut prices and capture the demand, whereas a price lower than the average cost is not profitable since a firm would not be able to cover its fixed costs anymore. If several firms are in the market and charge the same price, a firm is randomly selected to serve the whole market. Furthermore, if a firm does not capture the whole market demand, this firm can reduce the average cost and, therefore, the price by extending the production quantity. Consequently, only one firm will operate in this market and capture the whole market demand ($q_j = 1$).

This market structure is a Nash equilibrium because neither potential entrants nor the incumbent have the incentive to deviate from their strategies. On the one hand, the low product price of the incumbent deters potential entrants since they are not able to charge the same price without making losses. On the other hand, the incumbent cannot charge a price higher than the average cost without the threat of losing the whole market demand to a market entrant. Also, the incumbent will not charge a price below the average cost as discussed above.

$$p_{III} = \frac{F_j}{q_j} + c_j \tag{4}$$

$$M_{III} = 1 \tag{5}$$

Although the adoption of AM technology monopolises the market, the AM firm is compelled to charge the lowest possible price leading to zero profits.[5] Thus, it can be argued

[5] While it is plausible to assume this kind of competition, technical features of AM technology, e.g. slow printing speed and limited building speed, or market characteristics, e.g. market entry barriers, could affect the strategic behaviour of firms with digital factories. In order underline the results of this

that the market of market III is contestable (Baumol et al. 1982, 1983). Following the definition of Baumol et al. (1982), a contestable market is a market where the credible threat of entry forces firms in the market to behave in a competitive manner.

3.2.3 Market II

In market II, there is a coexistence of firms with traditional factories employing TM technologies and firms with digital factories employing AM technologies. The analysis starts with the derivation of the market share of firm i and j in order to subsequently determine the prices and the number of firms in the market.

Market Shares

In market II, a consumer can choose between either a standardised product from a traditional factory or a customised product from a digital factory. Consumer l chooses to buy the product from the firm which provides the highest utility given the following utility function.

$$U_l = \begin{cases} v - p_i - t|x_i - x_l|, & \text{if product } x_i \text{ is consumed} \\ v - p_j, & \text{if product } x_j \text{ is consumed} \end{cases}$$

Consuming the product of firm j does not cause any transportation cost because digital factories customise their products to exactly match the consumer's preference. Hence, $x_j = x_l$ for all $j \in M$ and all $l \in L$. Firms of the digital sector place their product variants in the space between the product locations of two traditional factories, where consumers must pay particularly high transportation costs (Weller et al. 2015, Kleer & Piller 2019). In order to illustrate firms' product positioning, Figure 1a visualises the product locations of four firms with traditional factories and one firm with a digital factory. Figure 1b represents the market demand for firm i and j given their product prices. Following the analysis of market I, the market demand for firm i and j can be determined by identifying the marginal consumer. The marginal consumer at the location $\tilde{x}$ is defined as the consumer who is indifferent between the consumption of the products offered by both firms i and j at the locations x_i and x_j (see figure 1b). Setting $U_l(x_i) = U_l(x_j)$ allows to determine the marginal consumer.

$$U_l(x_i) = v - p_i - t|x_i - x_l| = v - p_j = U_l(x_j) \qquad \leftrightarrow \qquad \tilde{x} = \frac{p_j - p_i}{t}$$

All consumers between x_i and $\tilde{x}$ buy the product from firm i because they gain the highest

study, I do not consider these features for the sake of simplicity and analyse the best case for social welfare.

utility from this product. Due to symmetry, firm i captures the demand of twice this distance (see figure 1b). Hence, the demand for products of firm i and consequently its production quantity is $q_i = 2\tilde{x}$.

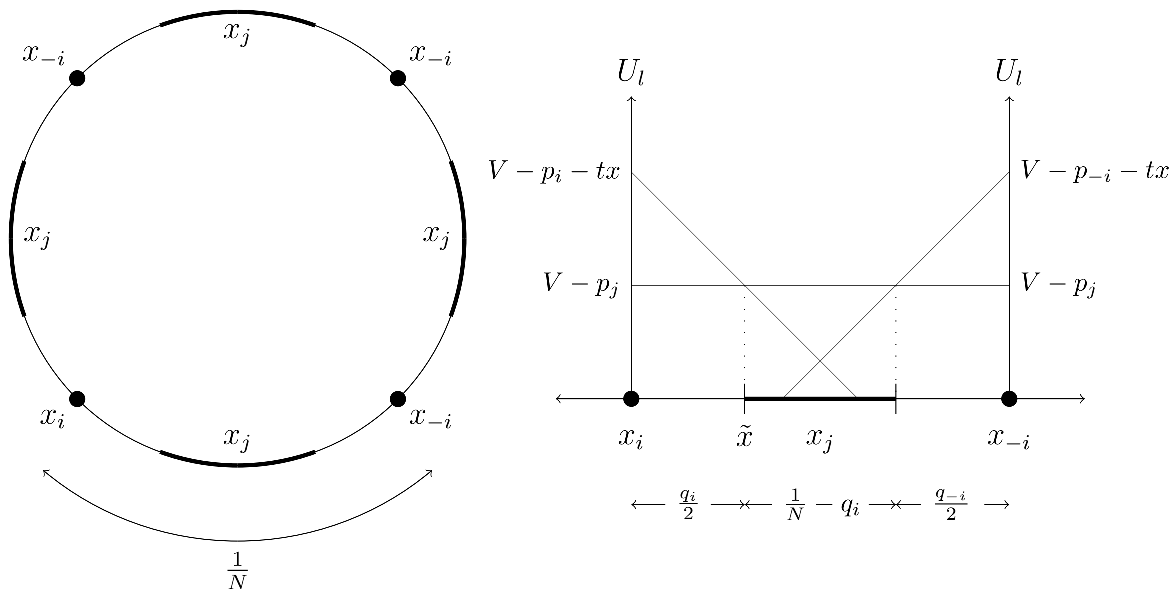
$$q_i = \frac{2(p_j - p_i)}{t} \tag{6}$$

From the demand for firm i, the market share Q_k of the traditional and digital sector can be derived. The market share of the traditional sector is the total production quantity of all traditional factories. Consequently, the digital sector captures the rest of the market demand.

$$Q_i = \frac{2N(p_j - p_i)}{t} \tag{7}$$

$$Q_j = 1 - \frac{2N(p_j - p_i)}{t} \tag{8}$$

The equations of the market shares show that an increase in the transportation cost decreases the market share of the traditional sector (Q_i) while, ceteris paribus, an increase in the number of traditional factories and the price difference between firm j and i increases the market share. In contrast, the impact of these variables on the market share of the digital sector (Q_j) have the opposite effects.



(a) Product space

(b) Demand for firm k

Figure 1: Competition in market II

Equilibrium Prices

The analysis of product prices in the equilibrium examines the profit maximising long-run prices for firms in both the traditional and digital sector. Due to the circumstance that firms with digital factories place their product variants into the niches between the locations of the products of two neighbouring traditional factories (see Figure 1a), the closest product variant of firm i's competitors is a product from firm j. Thus, firm i chooses a price which maximises its profits by only taking the price of firm j into account. Incorporating the demand function of firm i (eq. 6) into the profit function (eq. 1) and maximising it with respect to price i leads to the best response function of firm i.

$$p_i = \frac{c_i + p_j}{2} \tag{9}$$

Firm i's best response function describes the profit optimising product price (p_i) with regard to the price of firm j. In the long-run, firms with traditional factories choose a price that provides zero profits and is a best response to the price of firm j. Applying the zero-profit assumption and inserting the best response (eq. 9) and demand function of firm i (eq. 6) into the profit function (eq. 1) leads to the long-run equilibrium price of firm j.

$$\Pi_i \overset{!}{=} 0 \qquad \leftrightarrow \qquad p_j = \sqrt{2F_i t} + c_i \tag{10}$$

Substituting the long-run equilibrium price of firm j (eq. 10) into the best response function of firm i (eq. 9) yields the long-run equilibrium price of firm i.

$$p_i = \sqrt{\frac{F_i t}{2}} + c_i \tag{11}$$

In the equilibrium, the prices of both industries depend on the transportation cost, fixed cost, and marginal cost of firm i, like in market I. An increase in one of these costs leads, ceteris paribus, to higher product prices. Moreover, firm j charges a higher price than firm i. In order to compare the product prices among the three market scenarios, the average market price of market II is calculated. The average market price is the arithmetic mean of all product prices. If the market is cleared, the total output is equal to 1, which allows to determine the average market price as follows:

$$\overline{p_{II}} = \sum_{k \in K} p_k q_k = p_i Q_i + p_j Q_j \qquad \leftrightarrow \qquad \overline{p_{II}} = p_{IIj} - F_i N_{II} \tag{12}$$

The average market price depends on the product price of firm j and is negatively associated with the accumulated fixed cost of the traditional sector. A higher number of traditional factories is therefore reducing the average product price.

Number of Firms

The number of traditional factories (N) is used as a measure for the market concentration because of the negligible small number of firms in the digital sector. From market III, it is known that only one firm operates in the digital sector. Due to the threat of entrants, the firm with the digital factory charges a price equal to the average cost. Hence, the AM firm captures a demand that exactly covers its fixed costs given its long-run product price (eq. 10).

$$p_j = c_j + \frac{F_j}{q_j} \qquad \leftrightarrow \qquad q_j = \frac{F_j}{\sqrt{2F_i t} - (c_j - c_i)} \tag{13}$$

In other words, firms with traditional factories enter the market until the firm with the digital factory only obtains the required demand. Thus, the number of firms with traditional factories can be determined by inserting the best response function of firm i (eq. 9), short-run price (eq. 4), and production quantity of firm j into the market share formula of the digital sector (eq. 8).

$$N = \sqrt{\frac{t}{2F_i}} \left(1 - \frac{F_j}{\sqrt{2F_i t} - (c_j - c_i)} \right) \tag{14}$$

The number of firms with traditional factories depends on the transportation cost and the cost structures of firm i and j. An increase in transportation cost or fixed cost of firm i increases, ceteris paribus, the number of firms with traditional factories. In contrast, an increase in fixed cost of firm j or the marginal cost difference between firm j and i decreases, ceteris paribus, the number of firms with traditional factories.

3.3 Social Welfare

The following part addresses the long-run welfare implications of AM adoption. The welfare analysis lays the foundation to answer two questions: First, how does the digitalisation change social welfare? Second, is the product variety in the different market equilibria socially efficient?

3.3.1 Consumer Surplus

The social welfare encompasses the sum of all consumers surpluses and firms profits. Due to the zero-profit assumption, the producer surplus is equal to zero. Therefore, the total social welfare corresponds to the total consumer surplus. Consumer surplus describes the consumer's benefits from consuming a product, which is defined by the difference between consumer's willingness to pay (v) and their costs (Belleflamme & Peitz 2015). The costs depends on the consumed product type. While consumers must pay a product price (p_i) and transportation cost (t) for each travelled distance unit (x) if they consume a standardised product from a traditional factory, they only need to pay a product price (p_j) if they purchase a customised product from an digital factory. Figure 2 visualises the share of consumer surplus, transportation costs, and product price on gross utility of each consumer within the space between two firms with traditional factories for market I (Figure 2a), market II (Figure 2c), and market III [6] (Figure 2d). As seen in this illustration, the transportation costs are constantly decreasing while the market structure transforms from market I over market II to market III. Thus, the key question is whether the elimination of transportation cost through customised products can pay off for changes in the number of traditional firms and product prices in market II and market III.

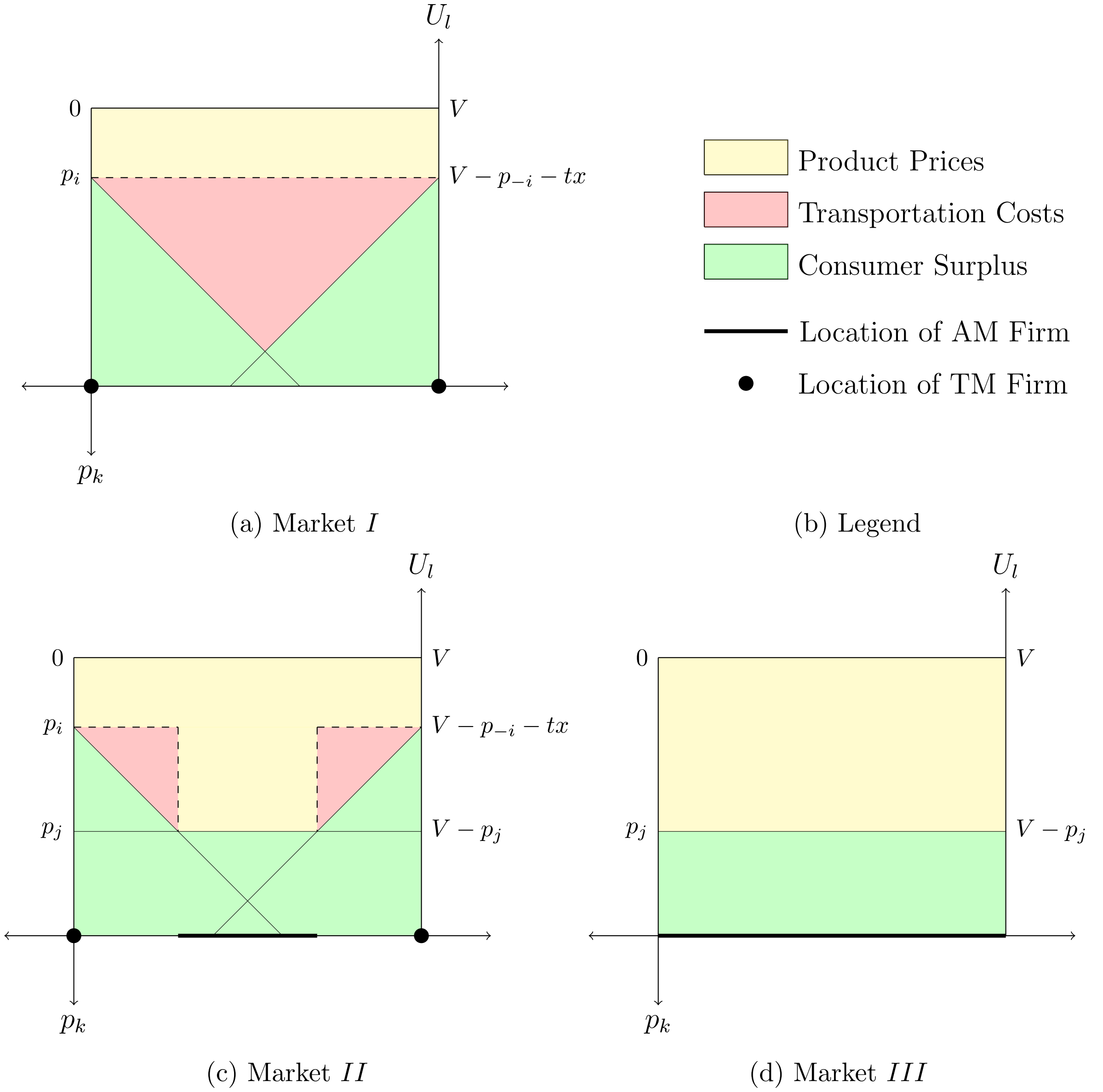
In order to determine the total consumer surplus (CS), the following formula can be taken to aggregate the utility of all consumers around the circle:

$$CS = 2N \int_0^{\frac{1}{2}q_i} (v - p_i - tx)dx + N \int_0^{\frac{1}{N}-q_i} (v - p_j)dx$$

In this formula, each component represents the total consumer surplus from the product of one sector. Since $v - p_i - tx$ is not continuous in the domain $[0, q_i]$, consumer's utility from products of the traditional sector is aggregated over $[0, \frac{q_i}{2}]$. The calculation for consumer surplus in market I, market II, and market III differs only in the range of aggregation and the number of firms with traditional factories. In the following, the consumer surplus for each market is calculated.

$$CS_I = v - p_I - \frac{t}{4N_I}$$
$$CS_{II} = v - p_{IIj} + \frac{N_{II}F_i}{2}$$
$$CS_{III} = v - p_{III}$$

[6] It should be noted that no firms with traditional factories exists in market III. Therefore, the illustration depicts an arbitrary range of the circle.



(a) Market I (b) Legend

(c) Market II (d) Market III

Figure 2: Share of consumer surplus and costs on gross utility

Market I represents the same results as in Salop (1979), where the consumer reservation price and number of firms have a positive impact on consumer surplus while market price and transportation cost have a negative effect. In market II, the consumer reservation price, number of firms with traditional factories, and fixed cost of firm i have a positive impact on consumer surplus while the price of firm j has a negative influence. In market III, the consumer surplus depends only on consumer's reservation and product price.

3.3.2 Product Variety

In a market, the resulting product variety $\lambda \in [0, 1]$ depends on the adopted technologies. In market I, the scope of product variants is based on the number of firms, as each firm creates one product variant. Salop (1979) shows that the number of product variants is socially inefficient in this market because more firms are entering the market than the social optimum intends. In market III, each consumer receives a customised product leading to the highest possible number of product variants. According to Baumol et al. (1982), a contestable market leads to a sustainable allocation and thus maximises social welfare. In market II, the product variety depends on the number of firms with traditional factories and their production quantity. In contrast to market I, an increase in the number of firms with traditional factories reduces, ceteris paribus, the product variety because more consumers forego to buy a customised product and purchase instead a standardised good.

In order to determine whether the product variety is socially optimal or not, the choice of a social planner is considered. A social planner wants to minimise market inefficiencies in order to maximise social welfare. In market II, there are three types of inefficiencies: First, the consumption of a standardised product which does not match with consumer's favourite product variant causes transportation cost. Second, the adoption of two different technologies can imply marginal cost differences in production. In other words, the production with one technology is more expensive than the other one. Third, each firm incurs entry costs and thereby exploits resources that could be attributed to the consumer surplus or producer surplus. Therefore, every additional firm is a welfare burden by increasing the aggregated sum of fixed costs (Salop 1979). The following welfare function considers these market inefficiencies and represents the total social welfare including the consumer and producer surplus.

$$W = 2N\int_0^{\frac{1}{2}q_i}(V-c_i-tx)dx + N\int_0^{\frac{1}{N}-q_i}(V-c_j)dx - NF_i - MF_j$$

Maximising the social welfare function with respect to the quantity of firm i allows to determine the optimal quantity q_i^o that maximises social welfare.

$$\frac{\delta W}{\delta q_i} \stackrel{!}{=} 0 \quad \leftrightarrow \quad q_i^o = \frac{2}{t}(c_j - c_i)$$

A comparison between the actual quantity (eq. 6) and the optimal quantity of firm i shows that the price difference must be equal to the marginal cost difference between firm j and firm i in the social optimum.

3.4 Existence conditions

The existence of market I, II, and III depends on firms' incentive to adopt AM technology. Firms are willing to invest in this technology if the resulting cost and market structure enable a profitable business. A profitable business implies a demand greater than zero (hereinafter demand condition) and non-negative profits (henceforth profit condition). Market I exists if the production with a AM technology in a digital factory does not lead to the fulfillment of both the demand and profit condition. In order to define the conditions when firms start to invest in digital factories, contemplate firm's strategic considerations to adopt AM technology in market I. As a potential entrant with a digital factory, the firm solely competes against firms with traditional factories. In other words, the potential entrant with a digital factory maximise its profit given the product price of the firms with traditional factories. The best pricing strategy (best response function) of a firm with a digital factory can be calculated by using the demand function of firm j (eq. 8) and maximising the profits (eq. 1):

$$p_j = \frac{c_j + p_i}{2} + \frac{t}{4N}.$$

Substituting the best response function of firm j into the best response function of firm i (eq. 9) and vice versa leads to the prices of firm i and j in the short-run:

$$p_i = \frac{1}{3}\left(2c_i + c_j + \frac{t}{2N}\right) \tag{15}$$

$$p_j = \frac{1}{3}\left(c_i + 2c_j + \frac{t}{N}\right). \tag{16}$$

The short-run prices describe firms' equilibrium product prices given a certain number of firms with traditional factories in the market. Even though the firm with the digital factory would force the firms in the traditional sector to adjust the prices because of a fiercer price competition, the number of traditional factories would remain the same in the short-run. From the market share function of the digital sector (eq. 8), it is known that the price difference between firm j and i ($p_j - p_i$) must be smaller than $\frac{t}{2N}$ in order that firm j captures any demand from the consumers. Taking into consideration the short-run equilibrium prices of firm i (eq. 15) and j (eq. 16) as well as the number of firms with traditional factories (eq. 3), the demand condition can be derived as follows:

$$p_j - p_i < \frac{t}{2N} \qquad \leftrightarrow \qquad c_j - c_i < \sqrt{F_i t}. \tag{17}$$

A firm only invest in a digital factory if the expected profits exceed or are equal to the fixed costs of the market entry (Weller et al. 2015). Thus, the profit condition of firm j can be identified by incorporating the demand function of firm j (eq. 8), short-run prices of firm i (eq. 15) and j (eq. 16), as well as the number of firms with traditional factories (eq. 3) into the profit function of the AM firm (eq. 1):

$$\Pi_j \overset{!}{\geq} 0 \qquad \leftrightarrow \qquad c_j - c_i \leq \sqrt{F_i t} - \sqrt{\frac{9}{2} F_j \sqrt{F_i t}}. \tag{18}$$

If the cost structure of a firm satisfies these conditions, this firm adopts AM technologies, and market I stops to exist.
The adoption of AM technologies leads either to market II or market III depending on the profitability of traditional factories. Market II occurs if firms can still realise a profitable business with TM technology, otherwise market III emerges. In order to determine the demand and profit condition of the traditional sector, assume that the firm with the digital factory behaves as a monopolist. In other words, the firm with a digital factory charges a price equal to the average cost to capture the whole market demand ($q_j = 1$). From the market share function of the traditional sector (eq. 7), it is known that the price difference between firm j and i ($p_j - p_i$) must be a greater than zero in order that firm i captures any demand. This implies that the price of firm j must be higher than the price of firm i. The demand condition of firm i can be determined by using the price of firm j (eq. 4) and the best response function of firm i (eq. 9):

$$0 < p_j - p_i \qquad \leftrightarrow \qquad -F_j < c_j - c_i.$$

The profit condition of firm i is calculated by inserting the demand function (eq. 7), best response function of firm i (eq. 9), as well as the price of firm j (eq. 4) into the profit function of firm i (eq. 1):

$$\Pi_i \overset{!}{\geq} 0 \qquad \leftrightarrow \qquad \sqrt{2F_i t} - F_j \leq c_j - c_i. \tag{19}$$

As a result of firm i's and j's profit condition, market II emerges if the marginal cost difference between firm j and i lies within the following range:

$$c_j - c_i \in \left[\sqrt{2F_i t} - F_j, \sqrt{F_i t} - \sqrt{\frac{9}{2} F_j \sqrt{F_i t}} \right]. \tag{20}$$

However, this prerequisite is only possible if there is no contradiction between the range limits. There is no conflict between the lower and upper limit if the following condition is satisfied:

$$F_j > a\sqrt{F_i t} \quad , \text{where } a = \frac{1}{4}\left((5+4\sqrt{2}) + \sqrt{9+72\sqrt{2}}\right) \tag{21}$$

Henceforth, this inequality is denoted as fixed-cost condition. Substituting the fixed-cost condition into the profit condition of firm i (eq. 19) and j (eq. 18) shows that the value of the marginal cost difference between firm j and i is negative. In other words, the marginal cost of firm j (c_j) is lower than the marginal cost of firm i (c_i) in market II.

3.5 Market comparison

A comparison of the market results allows to draw inferences about the effect of AM adoption on market structure and social welfare. In the following, the number of firms with traditional factories, average product prices, and consumer surplus are compared between the three markets.

3.5.1 Number of firms with traditional factories

Comparing the number of firm with traditional factories in market I and market II (Table 1) leads to the following condition.

$$N_I \gtreqless N_{II} \qquad \leftrightarrow \qquad \sqrt{2F_i t} + \frac{1}{\sqrt{2}-1}F_j \gtreqless c_j - c_i$$

From this condition, I can conclude that less firms with traditional factories exists in market II than in market I because it would violate the profit condition of firm j (eq. 18) otherwise. The welfare comparison shows that less than 33% of the firms with traditional factories survive the emerging competition with digital factories. The number of traditional factories is higher in market II than in market III by definition of the markets. Overall, the comparison between the number of firms with traditional factories indicate a rise in the market concentration. This development is caused by a reduction of firms with traditional factories represented in Figure 3.

	$Market_I$	$Market_{II}$	$Market_{III}$
N	$\sqrt{\frac{t}{F_i}}$	$\sqrt{\frac{t}{2F_i}}\left(1 - \frac{F_j}{\sqrt{2F_i t} - (c_j - c_i)}\right)$	0

Table 1: Overview: Number of firms with traditional factories

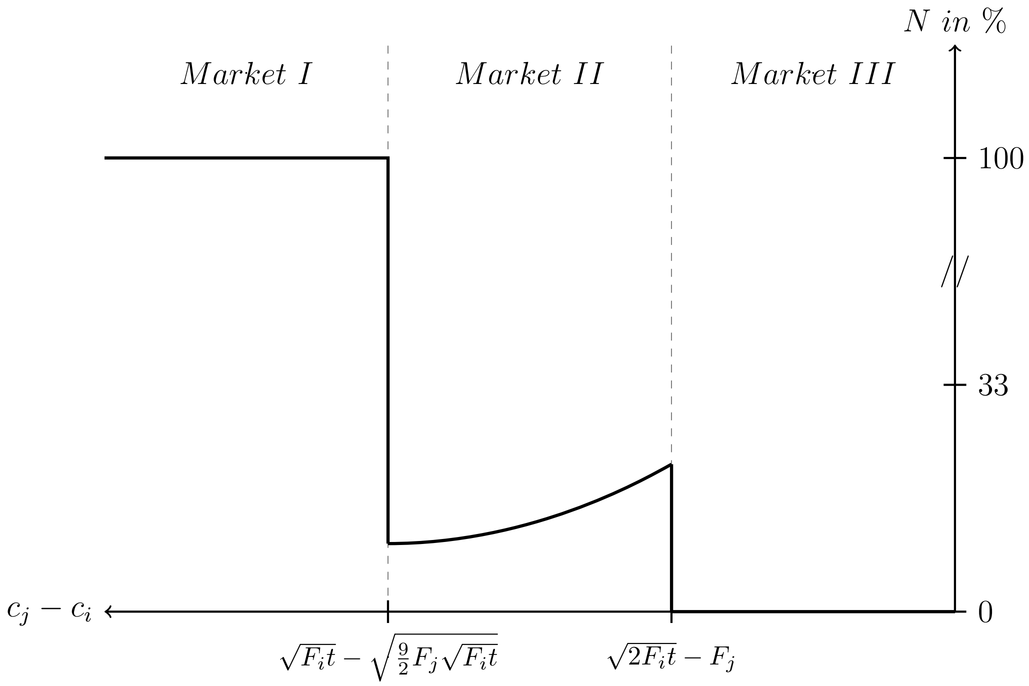


Figure 3: Effect of AM adoption on the number of firms with traditional factories

3.5.2 Product price

The effect of AM adoption on product prices depend on the cost structure of the technologies and emergent market. A comparison between the average product price in market I and market II (see Table 2) results in the following condition:

$$\overline{p_I} \gtreqless \overline{p_{II}} \qquad \leftrightarrow \qquad N_{II} \gtreqless (\sqrt{2} - 1) N_I.$$

The economic intuition behind this condition is a decline in the average product price if more than $\sqrt{2} - 1 \approx 41\%$ of the firms with traditional factories remain in the market. Since less than 33% of the firms with traditional factories remain in the market, I conclude that the average product price in market II is higher than in market I. The comparison between market I and market III (see Table 2) implies the following condition:

$$\overline{p_I} \gtreqless \overline{p_{III}} \qquad \leftrightarrow \qquad \sqrt{F_i t} - F_j \gtreqless c_j - c_i.$$

This condition indicate a cut-off, where the production with only one digital factory leads to lower product prices than a market with several traditional factories. This cut-off implies a decrease in product prices if the cost structure of digital factories is relatively cheap compared to traditional factories. Comparing market II with III (See Table 2) leads to the following condition:

$$\overline{p_{III}} \gtreqless \overline{p_{II}} \qquad \leftrightarrow \qquad \sqrt{2F_it} - F_j - F_iN_{II} \gtreqless c_j - c_i.$$

Considering the profit condition of firm i (eq. 19), this condition indicates a higher product price in market III than in market II if the marginal cost difference between firm j and firm i is within the existence range of market II (eq. 20). The average product price change in dependence of the marginal cost difference between firm j and firm i is visualised in Figure 4.

	$Market_I$	$Market_{II}$	$Market_{III}$
Firm i (p_i)	$\sqrt{F_it} + c_i$	$\sqrt{\frac{F_it}{2}} + c_i$	$-$
Firm j (p_j)	$-$	$\sqrt{2F_it} + c_i$	$F_j + c_j$
Average price ($\overline{p}$)	$\sqrt{F_it} + c_i$	$p_{IIj} - F_iN_{II}$	$F_j + c_j$

Table 2: Overview: Product prices

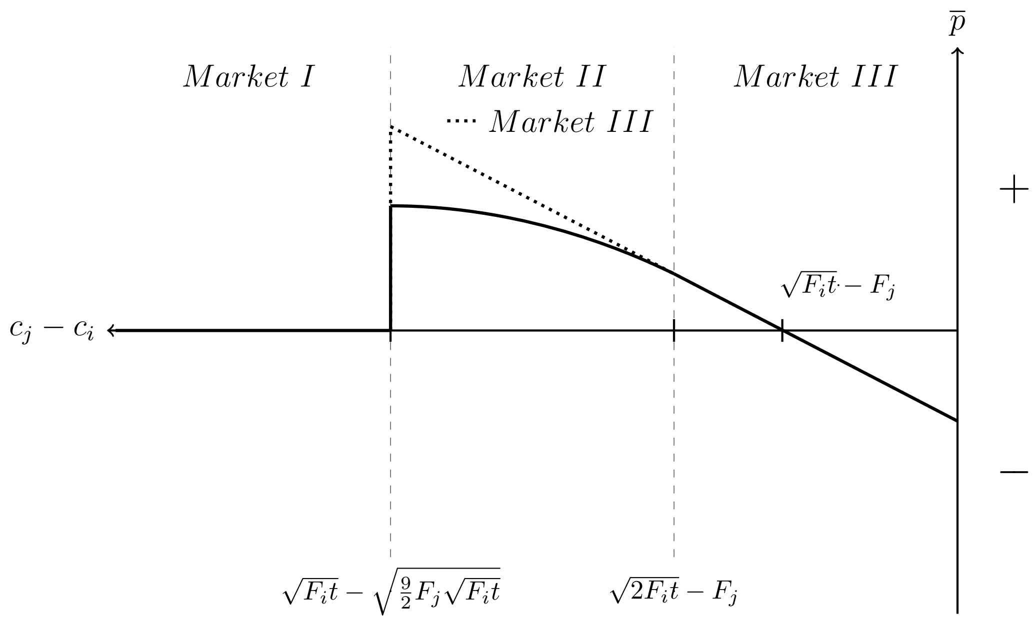


Figure 4: Effect of AM adoption on average product price

3.5.3 Consumer surplus

The effect on consumer surplus and therefore social welfare varies with the adopted technologies in a market. In markets where both AM and TM technologies are in use, an increase in consumer surplus depends on whether a higher product variety can compensate for higher product prices. Essentially, this trade-off is driven by the number of firms with traditional factories. Comparing the consumer surplus in market I and market II (see Table 3) leads to the following condition:

$$CS_I \gtreqless CS_{II} \qquad \leftrightarrow \qquad \frac{-5+4\sqrt{2}}{2}N_1 \gtreqless N_{II}.$$

This condition shows an increase in consumer surplus in market II compared to market I if more than $\frac{-5+4\sqrt{2}}{2} \approx 33\%$ of the firms with traditional factories remain in the market. In order to verify whether the number of TM firms stays above or below this cut-off, the number of firms with traditional factories in market I (eq. 3) and market II (eq. 14) are plugged into the condition above.

$$CS_I \gtreqless CS_{II} \qquad \leftrightarrow \qquad c_j - c_i \gtreqless \sqrt{2F_it} - \frac{6+5\sqrt{2}}{7}F_j$$

This expression indicates a continuance of more than 33% of the initial firms with traditional factories if the marginal cost difference between firm j and firm i falls below $\sqrt{2F_it} - \frac{6+5\sqrt{2}}{7}F_j$. However, this threshold is smaller than the profit condition of firm i (eq. 19) implying that all firms with traditional factories would have left the market before reaching this threshold and the non-existence of market II. Thus, the consumer surplus of market I is higher than in market II. The comparison between market I and market III (See Table 3) implies the following condition:

$$CS_I \gtreqless CS_{III} \qquad \leftrightarrow \qquad c_j - c_i \gtreqless \frac{5}{4}\sqrt{F_it} - F_j.$$

In line with the effect on market price, the welfare comparison indicates a cut-off, where the production with only one digital factory leads to higher social welfare than the production with several traditional factories. Welfare gains already occur with a more expensive cost structure than a decline in prices. The comparison between consumer surplus in market II and market III (see Table 3) implies the following condition:

$$CS_{III} \gtreqless CS_{II} \qquad \leftrightarrow \qquad c_j - c_i \gtreqless \sqrt{2F_it} - F_j - \frac{1}{2}F_iN_{II}.$$

This condition shows a higher level of consumer surplus in market II than in III as long as the as the marginal cost difference between firm j and firm i is within the existence range of market II (eq. 20). Figure 5 illustrates the consumer surplus depending on the marginal cost difference between firm j and firm i.

	$Market_I$	$Market_{II}$	$Market_{III}$
CS	$v - p_I - \frac{t}{4N_I}$	$v - p_{IIj} + \frac{N_{II}F_i}{2}$	$v - p_{III}$

Table 3: Overview: Consumer surplus

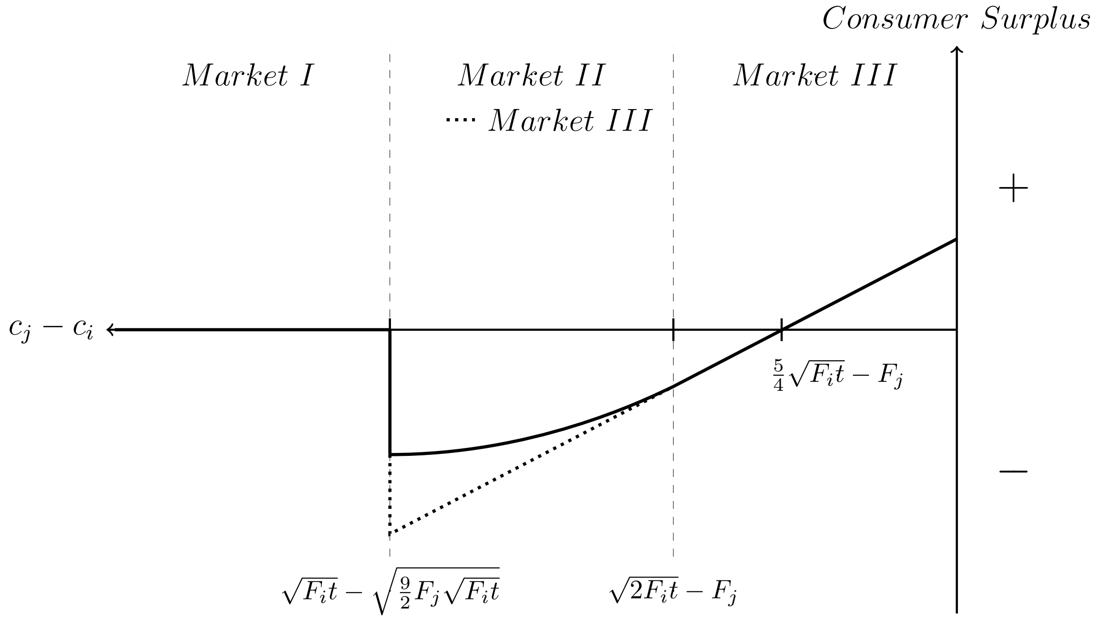


Figure 5: Effect of AM adoption on consumer surplus

4 Discussion

The aim of this article was to examine the impact of industrial AM adoption, and more broadly the emergence of digital factories, on competition and social welfare. While previous research discussed changes in market structure and social welfare in the short-run, this analysis was interested in the long-run consequences. With the analysis of the long-run effects, this article extents the model by Kleer & Piller (2019) and contributes to the prevailing discussion about market structure changes caused by the digitalisation of production facilities and provides insights for policy makers to support the transformation from traditional manufacturing towards digital manufacturing. In the following, I discuss and summarise the results in order to develop six propositions.

According to the analysis, a central driver for the adoption of AM technology is consumer's demand for a customised product. The demand and profit condition indicates a positive correlation between the transportation cost (t) and the likelihood of AM adoption. Moreover, higher transportation cost leads, ceteris paribus, to a higher market share for the digital sector. With a higher market share, a potential entrant is capable to cover the fixed cost earlier and build up a profitable business with a AM technology. This relationship is not surprising due to the characteristic of AM machines to flexible manufacture any product variant. Therefore, this comparative statics suggests the first proposition.

Proposition 1 *In markets with a high consumer need for product customisation, it is more likely that firms adopt AM technologies.*

In line with previous studies (Weller et al. 2015, Kleer & Piller 2019), the model results indicate significant changes in competition caused by AM adoption. Due to AM's production flexibility, firms with TM technology are exposed to fiercer competition leading to changes in the number of firms. According to the social welfare analysis, less than 33% of the traditional factories remain in a market. The exact number depends on various factors such as firms' cost structures and transportation cost. In general, the findings support previous research that discusses an increase in market concentration caused by the installation of flexible manufacturing technologies (Chang 1993, Eaton & Schmitt 1994, Norman & Thisse 1999). Furthermore, it supports the prediction of D'Aveni (2018) that AM adoption leads to the emergence of few giant manufacturers. This suggests the following:

Proposition 2 *The adoption of industrial AM technologies induces a decline in the number of firms with TM technologies and leads overall to a higher level of market concentration.*

In addition to a change in the number of firms, traditional firms adjust their product prices. As expected, the model result shows a decline in the product price of firms with traditional factories in the long-run. This price change is consistent with the results in Weller et al. (2015) and Kleer & Piller (2019). In contrast, firms with AM technology choose a product price above the initial price in the benchmark market. Firms with AM can charge a price premium, because they produce customised goods which do not cause any transportation costs for the consumers (Weller et al. 2015). Interestingly, the product price of firm j depends solely on the cost structure of firms with TM technology and transportation cost. In markets where both technologies are in use, the digital sector captures such a large market share that the average product price rises. However, if the market consists of only one firm with a digital factory, there is a cut-off where the adoption of AM reduces the product price. To summarise the discussion about price changes, the following proposition is suggested:

Proposition 3 *The adoption of AM leads to a rise of the average product price in markets where both AM and TM technologies exists for the production of goods. In markets where AM is the only production technology, there is a certain cost cut-off where average prices are lower than in markets with only traditional factories.*

The effect on consumer surplus and therefore social welfare varies with the adopted technologies. In markets where both AM and TM technologies are in use, an increase in consumer surplus depends on whether a higher product variety can compensate for a higher average price. Essentially, this trade-off is driven by the number of firms with TM technology. From the analysis, it can be concluded that the adoption of AM reduces social welfare in markets where both AM and TM technologies exists for the production of goods because the opportunity to consume expensive customised products does not compensate the decline in the variety of cheap standardised goods. This result contradicts with the third proposition of Kleer & Piller (2019), who claim a rise in consumer surplus in markets with a competition between manufacturer with TM and producers with AM technologies.

In markets with only one digital factory, the consumer surplus depends only on the product price. Since the AM monopolist charges a price equal to the average cost, marginal and fixed costs are crucial factors for the consumer surplus. The discussion about consumer surplus leads to the following proposition:

Proposition 4 *The adoption of AM induces a decline in social welfare in markets where firms employ both AM and TM technologies. In markets where AM is the only production technology, there is a certain production cost cut-off where the social welfare is higher than in markets with only TM technology.*

AM adoption has a significant impact on the product variety. Since all consumers of firms with AM receive their preferred variants, the product variety reaches the highest possible level in markets with only AM technologies. It can be argued that this market provides an optimal resource allocation because of its contestable market characteristics (Baumol et al. 1982, 1983). In contrast, the product variety is lower in markets with AM and TM technologies due to the supply of standardised products. Due to the fact that the marginal cost of firm j is lower than that of firm i, firm i does not produce any products in the social optimum. This implies that all consumers should receive their preferred product variants. Consequently, it can be concluded that market II leads to an inefficient market allocation. Therefore, this paper suggests:

Proposition 5 *In markets where both TM and AM technologies are employed for the production of goods, the market outcome leads to an inefficient resource allocation.*

Considering the market efficiency, it could be argued that markets with only AM are more preferable than markets with both AM and TM technologies. Nevertheless, the consumer surplus and thus total social welfare is higher in markets with TM and AM compared to markets with only AM if the marginal cost difference lies within the cost interval (eq. 20) where both markets can exist. Therefore, a social planner would support a production with TM in order to realise a second best optimum (Lipsey & Lancaster 1956) as long as the marginal costs difference lies within the the existence range of market II (eq. 20). Various government programmes financially support firms in the acquisition of digital technologies such as AM.[7] By providing acquisition boni, those funding programmes reduce firms' fixed costs and increase thereby the incentives to adopt AM technologies (see eq. 17 and eq. 18). Yet, a reduction in the fixed costs also reduces the likelihood to satisfy the fixed-cost condition (eq. 21). If the marginal cost of AM technologies is in addition not sufficiently low, fixed-cost-reducing funding programmes cause welfare losses by disincentivising firms to operate with TM technologies. Another way to encourage the adoption of AM technologies is to implement a funding programme that reduces the marginal costs of the production with AM. By doing so, firms are more willing to invest in TM technologies reducing the average product prices, which in turn leads to higher social welfare than fixed-cost-reducing funding programmes. As a consequence of the model presented in this paper, policy makers should rather consider policy measures to reduce marginal costs rather than fixed costs of AM technologies. This policy recommendation is in line with findings from previous studies (Peters et al. 2017). From this discussion, I derive the following proposition:

Proposition 6 *In the stimulation of AM technologies, Marginal-cost-reducing funding programmes create higher expected welfare gains than fixed cost reducing funding programmes.*

The AM process requires three main input factors comprising raw material, energy, and a digital design data. The production cost of AM mainly consists of machine [8], labour, and material costs. Other components such as energy consumption and rental space do not contribute significantly to the cost structure (Hopkinson & Dicknes 2003, Thomas 2016). Therefore, marginal costs are mainly driven by the price of materials and labour while fixed costs consists of the machine expenditures. Consequently, a welfare maximising funding programme for AM technologies could entail research and development subsidies directed at reducing marginal costs for instance through materials or automation.

5 Conclusion

The results from the game-theoretical model show a decline in the number of firms with TM technology and a rise in market concentration in response to AM adoption. Furthermore, the model indicates potential enhancements in social welfare. However, changes in

[7] See for example https://www.bmwi.de/Redaktion/DE/Dossier/digital-jetzt.html and https://www.aws.at/corona-hilfen-des-bundes/aws-investitionspraemie/

[8] Machine cost is the sum of the annual cost for machine maintenance and equipment depreciation (Hopkinson & Dicknes 2003).

product prices and social welfare depend on AM's production costs and yield a negative effect if the costs of manufacturing are high. Therefore, this paper highlights the important role of production costs with AM not only for its adoption but also for product prices and social welfare. Furthermore, it demonstrates the relevance of TM technologies in the transformation from traditional manufacturing towards a digital manufacturing. In order to verify the propositions of this paper, future research should conduct quantitative analyses. Besides AM, there are further digital technologies increasing the production flexibility of factories as well. Even though they are not explicitly considered in this paper, the results can be generalised for other emerging technologies which facilitate a flexible production.

The model presented here benefits from is a simplification of reality and is consequently subject to several limitations. Considering these limitations is crucial for a reasonable interpretation of the findings since they might have a profound impact on the results and policy implications. In general, it can be distinguished between limitations from model assumptions about market supply and demand. On the supply side, a potential limitation is the assumed cost structure of a firm with AM technology. In order to deal with complexity and to obtain insights about AM adoption on the industrial level, this paper focuses merely on AM's capability to flexibly manufacture various products, but it does not take into account other essential AM characteristics such as the capability to manufacture products with a higher quality. In addition, the model restricts the product variety with AM to only one market. Nevertheless, a firm with AM may produce goods in various markets. Further research could extend the model by considering the aspects that AM requires less material than TM technologies and the potential to produce goods with higher quality, e.g. new product designs with lightweight structures, or the ability to manufacture products for different markets.

On the demand side, the main challenge is to model consumers' needs. Here, a critical limitation is the assumption of an inelastic market demand. Certainly, there are some markets where the price elasticity is rather inelastic than elastic, e.g. in the medical and aerospace industry. Nevertheless, such consumer behaviour may be reality in all markets. In markets with high price elasticity, expensive customised products might impede the adoption of AM. Hence, future research should consider different price elasticities to better understand the obstacles of AM adoption in these markets. In addition, this model underlies the assumption of a predictable market demand. Yet, markets nowadays exhibit increasingly higher uncertainty in demand due to globalisation and complex supply chains. Consequently, demand uncertainty and fluctuation could incentivise the adoption of AM. In order to gain more insights about AM adoption, a future model could implement uncertainty and fluctuations in demand.

Despite these limitations, the analysis extends our knowledge about the digitalisation of the manufacturing industry and contributes valuable insights for policy measures. Recent debates on the future of AM discusses its role for manufacturing. Experts predominantly expect AM to rather complement than substitute TM technologies (Attaran 2017). In this future scenario, market structure changes as a result of the AM adoption lead to welfare losses. From a welfare point of view, it is, therefore, desirable to stimulate AM adoption. However, the type of stimulation is an important factor for an efficient governmental support. While fixed cost reducing funding programmes bear the risk of disincentivising firms to employ TM technologies even though they are essential for a welfare maximising production, marginal cost reducing funding programmes do not cause the risk of over-adoption and leads to a digital transformation with a higher expected state of social welfare. In order to reduce marginal costs, an efficient funding programme could support the research and development of materials for the production with AM technologies.

References

Attaran, M. (2017), 'The rise of 3-d printing: The advantages of additive manufacturing over traditional manufacturing', *Business Horizons* **60**(5), 677–688.

Bai, C., Dallasega, P., Orzes, G. & Sarkis, J. (2020), 'Industry 4.0 technologies assessment: A sustainability perspective', *International Journal of Production Economics* **229**, 107776.

Baumers, M. & Holweg, M. (2019), 'On the economics of additive manufacturing: Experimental findings', *Journal of Operations Management* **65**(8), 794–809.

Baumol, W. J., Panzar, J. C. & Willig, R. D. (1982), *Contestable Markets and the Theory of Industry Structure*, Harcourt Brace Jovanovich, San Diego.

Baumol, W. J., Panzar, J. C. & Willig, R. D. (1983), 'Contestable markets: An uprising in the theory of industry structure: Reply', *The American Economic Review* **73**(3), 491–496.

Belleflamme, P. & Peitz, M. (2015), *Industrial Organization: Markets and Strategies*, Cambridge University Press, Cambridge.

Bernhardt, D., Liu, Q. & Serfes, K. (2007), 'Product customization', *European Economic Review* **51**(6), 1396–1422.

Chamberlin, E. H. (1949), *The Theory of Monopolistic Competition: A Re-Orientation of the Theory of Value*, Harvard University Press, Cambridge, MA.

Chang, M.-H. (1993), 'Flexible manufacturing, uncertain consumer tastes, and strategic entry deterrence', *The Journal of Industrial Economics* **41**(1), 77–90.

Dalenogare, L. S., Benitez, G. B., Ayala, N. F. & Frank, A. G. (2018), 'The expected contribution of industry 4.0 technologies for industrial performance', *International Journal of Production Economics* **204**, 383–394.

D'Aveni, R. A. (2018), *The Pan-Industrial revolution: How New Manufacturing Titans will Transform the World*, Houghton Mifflin Harcourt, Boston, MA.

Delic, M. & Eyers, D. R. (2020), 'The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry', *International Journal of Production Economics* **228**, 107689.

Dewan, R., Jing, B. & Seidmann, A. (2003), 'Product customization and price competition on the internet', *Management Science* **49**(8), 1055–1070.

Dixit, A. K. & Stiglitz, J. E. (1977), 'Monopolistic competition and optimum product diversity', *The American Economic Review* **67**(3), 297–308.

Eaton, B. C. & Schmitt, N. (1994), 'Flexible manufacturing and market structure', *The American Economic Review* **84**(4), 875–888.

Eyers, D. R., Potter, A. T., Gosling, J. & Naim, M. M. (2018), 'The flexibility of industrial additive manufacturing systems', *International Journal of Operations and Production Management* **38**(12), 2313–2343.

Frank, A. G., Dalenogare, L. S. & Ayala, N. F. (2019), 'Industry 4.0 technologies: Implementation patterns in manufacturing companies', *International Journal of Production Economics* **210**, 15–26.

Gebhardt, A. & Hötter, J.-S. (2016), *Additive manufacturing: 3D Printing for Prototyping and Manufacturing*, Carl Hanser Verlag GmbH & Co. KG, Munich.

Ghobadian, A., Talavera, I., Bhattacharya, A., Kumar, V., Garza-Reyes, J. A. & O'regan, N. (2020), 'Examining legitimatisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability', *International Journal of Production Economics* **219**, 457–468.

Gibson, I., Rosen, D. & Stucker, B. (2014), *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, Springer, Berlin.

Gilchrist, A. (2016), *Industry 4.0: the industrial internet of things*, Springer, Berlin.

Goldfarb, A. & Tucker, C. (2019), 'Digital economics', *Journal of Economic Literature* **57**(1), 3–43.

Haleem, A. & Javaid, M. (2019), ‘Additive manufacturing applications in industry 4.0: a review’, *Journal of Industrial Integration and Management* **4**(04), 1930001.

Hopkinson, N. & Dicknes, P. (2003), ‘Analysis of rapid manufacturing—using layer manufacturing processes for production’, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **217**(1), 31–39.

Hotelling, H. (1929), ‘Stability in competition’, *The Economic Journal* **39**(2), 41–57.

Jiang, R., Kleer, R. & Piller, F. T. (2017), ‘Predicting the future of additive manufacturing: A delphi study on economic and societal implications of 3d printing for 2030’, *Technological Forecasting and Social Change* **117**, 84–97.

Karevska, S., Steinberg, G., Müller, A., Wienken, R., Kilger, C. & Krauss, D. (2019), 3d printing: Hype or game changer? a global ey report 2019, Technical report, Ernst & Young. Retrieved from https://www.ey.com/.

Kleer, R. & Piller, F. T. (2019), ‘Local manufacturing and structural shifts in competition: Market dynamics of additive manufacturing’, *International Journal of Production Economics* **216**(C), 23–34.

Lancaster, K. (1975), ‘Socially optimal product differentiation’, *The American Economic Review* **65**(4), 567–585.

Lipsey, R. G. & Lancaster, K. (1956), ‘The general theory of second best’, *The Review of Economic Studies* **24**(1), 11–32.

Milgrom, P. & Roberts, J. (1990), ‘The economics of modern manufacturing: Technology, strategy, and organization’, *The American Economic Review* **80**(3), 511–528.

Norman, G. & Thisse, J.-F. (1999), ‘Technology choice and market structure: Strategic aspects of flexible manufacturing’, *The Journal of Industrial Economics* **47**(3), 345–372.

Pérez-Pérez, M., Sebastián, M. & Gómez, E. (2021), Forecasting on additive manufacturing in spain: How 3d printing would be in 2030, *in* ‘Project Management and Engineering Research’, Springer, Berlin, pp. 333–349.

Peters, B., Roberts, M. J., Vuong, V. A. & Fryges, H. (2017), ‘Estimating dynamic r&d choice: an analysis of costs and long-run benefits’, *The RAND Journal of Economics* **48**(2), 409–437.

Roberts, T. & Varotsis, A. B. (2020), 3d printing trends 2020: Industry highlights and market trends, Technical report, 3D Hubs. Retrieved from https://www.3dhubs.com/get/trends/.

Röller, L.-H. & Tombak, M. M. (1990), 'Strategic choice of flexible production technologies and welfare implications', *The Journal of Industrial Economics* pp. 417–431.

Romer, P. M. (1990), 'Endogenous technological change', *Journal of Political Economy* **98**(5), 71–102.

Salop, S. C. (1979), 'Monopolistic competition with outside goods', *The Bell Journal of Economics* **10**(1), 141–156.

Sethi, A. K. & Sethi, S. P. (1990), 'Flexibility in manufacturing: A survey', *International Journal of Flexible Manufacturing Systems* **2**(4), 289–328.

Thomas, D. (2016), 'Costs, benefits, and adoption of additive manufacturing: A supply chain perspective', *The International Journal of Advanced Manufacturing Technology* **85**(5-8), 1857–1876.

Wang, S., Wan, J., Zhang, D., Li, D. & Zhang, C. (2016), 'Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination', *Computer Networks* **101**, 158–168.

Weller, C., Kleer, R. & Piller, F. T. (2015), 'Economic implications of 3d printing: Market structure models in light of additive manufacturing revisited', *International Journal of Production Economics* **164**(C), 43–56.

Previous Munich Papers in Political Economy:

Betz, Timm and Amy Pond. “Political Ownership”, MPPE No. 1/2020, Munich. (ISSN)2701-3456

Chatziathanasiou, Konstantin, Hippel, Svenja and Michael Kurschilgen. “Property, Redistribution, and the Status Quo. A laboratory study”, MPPE No. 2/2020, Munich. (ISSN)2701-3456

Becker, Annette, Hottenrott, Hanna and Anwesha Mukherjee. “Division of Labor in R&D? Firm Size and Specialization in Corporate Research”, MPPE No. 3/2020, Munich. (ISSN)2701-3456

Steinert, Janina Isabel, Satish, Rucha Vasumati, Stips, Felix and Sebastian Vollmer. “Commitment or Concealment? Impacts and Use of a Portable Saving Device: Evidence from a Field Experiment in Urban India, MPPE No. 4/2020, Munich. (ISSN)2701-3456

Messerschmidt, Luca and Nicole Janz. ”Unravelling the `race to the bottom' argument: How does FDI affect different types of labour rights?”, MPPE No. 5/2020, Munich. (ISSN)2701-3456.

Chowdhury, Subhasish M., Esteve-González, Patricia and Anwesha Mukherjee. ”Heterogeneity, Leveling the Playing Field, and Affirmative Action in Contests”, MPPE No. 6/2020, Munich. (ISSN)2701-3456

Drobner, Christoph. ”Motivated Beliefs and Anticipation of Uncertainty Resolution”, MPPE No. 7/2020, Munich. (ISSN)2701-3456

Chatziathanasiou, Konstantin, Hippel, Svenja and Michael Kurschilgen. “Do rights to resistance discipline the elites? An experiment on the threat of overthrow”, MPPE No. 8/2020, Munich. (ISSN)2701-3456

Siddique, Abu, Rahman, Tabassum, Pakrashi, Debayan, Islam, Asad, and Firoz Ahmed. "Raising COVID-19 Awareness in Rural Communities: A Randomized Experiment in Bangladesh and India”, MPPE No. 9/2020, Munich. (ISSN)2701-3456

Siddique, Abu. "Behavioral Consequences of Religious Education”, MPPE No. 01/2021, Munich. (ISSN)2701-3456

Vlassopoulos, Michael, Siddique, Abu, Rahman, Tabassum, Pakrashi, Debayan, Islam, Asad, and Firoz Ahmed. "Improving Women's Mental Health During a Pandemic”, MPPE No. 02/2021, Munich. (ISSN)2701-3456

March, Christoph, Schieferdecker, Ina.”Technological Sovereignty as Ability, not Autarky”, MPPE No. 03/2021, Munich. (ISSN)2701-3456

Hassan, Hashibul, Islam, Asad, Siddique, Abu, and Liang Choon Wang. "Telementoring and homeschooling during school closures: A randomized experiment in rural Bangladesh”, MPPE No. 04/2021, Munich. (ISSN)2701-3456

Angerer, Silvia, Dutcher ,Glenn, Glätzle-Rützler, Daniela, Lergetporer, Philipp, and Matthias Sutter. "The formation of risk preferences through small-scale events”, MPPE No. 05/2021, Munich. (ISSN)2701-3456

Hermes, Henning, Lergetporer, Philipp, Peter, Frauke and Simon Wiederhold. "Behavioral Barriers and the Socioeconomic Gap in Child Care Enrollment”, MPPE No. 06/2021, Munich. (ISSN)2701-3456

Schwierzy, Julian. “Digitalisation of Production: Industrial Additive Manufacturing and its Implications for Competition and Social Welfare”, MPPE No. 07/2021, Munich. (ISSN)2701-3456

Impressum:

ISSN: **2701-3456**
Editors: Tim Büthe, Hanna Hottenrott
Associate Editors: Timm Betz, Sebastian Goerg, Michael Kurschilgen, Amy Pond, Sebastian Schwenen, Janina Steinert, Matthias Uhl
Managing Editor: Luca Messerschmidt

Contact: Technicial University of Munich, Arcisstraße 21, 80333 München
mppe@gov.tum.de, mppe@wi.tum.de
https://www.wi.tum.de/mppe/
Twitter: @MunichPapers