ADDITIVE MANUFACTURING AND THE GLOBAL LOCALIZATION OF MANUFACTURING

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Abstract

Additive manufacturing (AM), also called 3D printing, has emerged as a transformative technology that is redefining traditional manufacturing industries. In this paper, we build on Markusen's (1995) Knowledge-Capital model of the multinational enterprise (MNE) to study the implications of AM for international business. We hypothesize that the adoption of AM technology increases the likelihood that MNEs co-locate production and consumption across the globe. Furthermore, we conjecture that an MNE's market scope positively moderates the relation between AM technology adoption and production-consumption co-location. To test our hypotheses, we rely on European Patent Office data to identify firms with AM-related patents and match this information to firm-level data of international production subsidiary networks from Bureau Van Dijk. Using both propensity score matching and zero-inflated negative binomial regressions, we find evidence supporting our theoretical predictions.

1 Introduction

Additive manufacturing (AM), also known as 3D printing, is a rapidly emerging technology that employs computer-controlled processes to create three dimensional objects by depositing materials, usually in layers. Used in a growing number of industries including consumer electronics, healthcare, automotive, aerospace, and robotics, there are initial indications that it is transforming traditional manufacturing by promoting mass customization (Berman, 2012; Wang et al., 2017), strategic and operational flexibility (Brettel, Klein & Friederichsen, 2016), and the servitization of manufacturing (Baines et al., 2009).

It is thus not surprising that international business researchers have turned their attention to the implications of AM for global business, and more specifically for the configuration of global value chains (Laplume, Petersen & Pearce, 2016, Strange & Zucchella, 2017). A common prediction that has come out of these early studies is that Industry 4.0, which includes AM, introduces a new era of digital globalization that will profoundly alter the global trade and investment landscape (Azmeh, Foster & Echavarri, 2020; Buckley, 2021; Zhan, 2021). Yet scholarship has remained vague on the specific ways how AM influences global business, to a large extent due to a paucity of empirical studies.

Two recent empirical papers have in this respect invigorated the debate on the nexus between AM and global business by providing evidence that companies which innovate in 3D printing technologies tend to deepen their degree of internationalization. In a study of 114 European companies that have revised their offshore location decisions, Barbieri et al. (2022) found that firms which had developed Industry 4.0 innovations were more likely to keep or expand their production internationally. In a large-scale study of global production subsidiary networks, De Beule et al. (2022) found that firms with AM patents have more foreign production subsidiaries than non-AM firms and operate them in more countries. These findings nonetheless fail to address the question how AM changes the configuration of global business activities, a lacuna that is especially striking in light of the widespread industry

transformations that technology management studies have documented and predicted (Baines et al., 2009; Berman, 2012; Brettel et al., 2016; Wan et al., 2017).

The aim of this paper is to tackle the question how AM drives the reconfiguration of global MNE activities head on. Building on the insights of Markusen's Knowledge Capital model of the multinational enterprise (Markusen, 1995), we theorize that AM and its ability to generate mass customization is driving a return of the "horizontal multinational", where manufacturing firms decentralize their production and localize their plants at or near the point of end-user consumption. That is, we hypothesize that AM increases the likelihood that manufacturing firms co-locate production and consumption across the globe. In addition, we propose that a manufacturing firm's market scope positively influences the relation between the adoption of AM technology and the co-location propensity.

To empirically study these questions, we have constructed a firm-level dataset of manufacturing companies from Bureau Van Dijk's Orbis data. We have next relied on the European Patent Office's PATSTAT database to determine which of those manufacturing companies have developed AM-related patents, allowing us to distinguish between additive manufacturers (treatment group) and other firms (control group). We focus on AM – also known as 3D printing – since it is one of the technologies related to industry 4.0 that has most profoundly affected international business (Banalieva & Dhanaraj, 2019; Bouncken & Barwinski, 2020; Buonafede et al., 2018; De Beule et al., 2022; Laplume et al., 2016; Strange & Zucchella, 2017).

Giving a preview of our main findings, we show that the adoption of AM technology increases the likelihood that manufacturing firms co-locate production and consumption around the world. We also find that market scope positively moderates the relationship between the adoption of AM technology and production-consumption co-location.

The paper is structured as follows. We will first construct a literature review describing the key tenets of the theory of the multinational firm and how additive manufacturing affects the theories underlying

assumptions. We will subsequently build our hypotheses, related to the impact of AM on production localization. Next, we will describe our dataset and its rationale before analyzing our regression results, which inform on our hypotheses. The article concludes by discussing the results in a broader light and outlining conclusions and future research avenues.

2 Background

To study how the adoption of AM technology influences the configuration of MNE activity, we build on insights from Markusen's Knowledge-Capital model of the MNE (Markusen, 1995). The framework, which is based on Dunning's OLI paradigm (Dunning, 1977), synthesizes within a single general-equilibrium framework models of "horizontal" market seeking FDI, where FDI is driven by the access to host-country markets, and models of "vertical" efficiency seeking FDI, where relative labor-endowment differences are the source of MNE expansion. It offers rich predictions about the different types of multinational firms that emerge in a global economy as functions of industry characteristics (factor intensities, scale economies, product differentiation) interacting with country characteristics (relative size differences, relative endowment differences, and trade costs).

The Knowledge-Capital model distinguishes between two main types of multinationals: horizontal and vertical MNEs. The fundamental difference between the two is one of duplication versus differentiation. A *horizontal MNE* duplicates key parts of its production process across multiple countries, taking the form of an octopus. For example, Hyundai may design its car in Korea and then use this blueprint to replicate the manufacturing of cars in the United States, Czech Republic, and China. While the cars are designed in one location (Korea), and thus, there is still an element of a supply chain in the firm's structure, the major part of its activities, here the manufacturing of the cars, is repeated in different countries. A *vertical MNE*, then again, performs different value chain activities across its different affiliates, fragmenting its production process, and creating the form of a snake. The classic example of a vertical MNE is an apparel company such as Nike. It designs apparel in the United

States, produces it in countries like China or Vietnam, and then ships it to a Nike-owned store in Europe for sale to consumers. This vertical structure is a natural embodiment of the global value chain with each step in the process contributing to a final good. The key to this structure is that each stage of the global value chain performs a different activity, with the different stages located in different countries.

The model predicts that three factors favor the development of horizontal over vertical MNEs: (1) a heightened similarity of relative factor endowments across countries; (2) a decline in plant scale economies; and (3) an increase in trade costs. To understand the importance of relative factor endowments, it is perhaps easiest to note that multi-plant firms (horizontal MNE) have an inherent disadvantage compared to single-plant firms when production costs are substantially lower in a country. Lower plant scale economies, then again, make horizontal multinationals more attractive by reducing the benefit of concentrating production in a single country. Higher trade costs make horizontal multinationals more attractive by eroding the cost advantage of concentrating production in a single country.

Empirical research has found consistent support for the predictions of the Knowledge Capital model (Braconier et al., 2005; Carr, Markusen & Maskus, 2003). At the same time, global trends have been unkind to the horizontal MNE compared to the vertical MNE. The integration of many developing countries, especially China, into the global trading system has introduced heightened differences in relative endowments across the globe. Adding to this, the importance of scale economies and mass production in traditional manufacturing as well as reductions in trade costs during the era of globalization has promulgated international production fragmentation and moved MNEs away from their traditional horizontal MNE form.

The question that we ask in this paper is whether the adoption of AM technology may lead to the return of the horizontal MNE, where companies globally localize production close to the consumers. This is a conjecture that is built on observations made by several studies without providing firm theoretical arguments or empirical evidence. Scholarship, for example, has pointed out that the rise

of AM technology holds the potential to “de-globalize” manufacturing of goods (Anderson, 2012; Campbell et al., 2011; D'Aveni, 2013). According to this view, the low cost of retooling and adjustments in AM production (Strange & Zucchella, 2017) could in time push firms to relocate from popular mass-production platforms such as China, Mexico, Eastern Europe and replicate production close to consumers (Campbell et al., 2011; Strange & Zucchella, 2017). The end result might well be mass customization, as opposed to the current mass-production paradigm (Anderson, 2012; Ben-Ner & Siemsen, 2017). However, it has been suggested that the impact of AM likely will vary by industry and product category (Holweg, 2015; Rehnberg & Ponte, 2018). And while it has been shown that there are differences in degree of production internationalization between various industries, they are all relatively more likely to internationalize production as compared to their non-additive manufacturing peers (De Beule et al., 2022). Accordingly, a thorough exploration of the theoretical channels through which AM influences the configuration of MNE activities is needed, and how it depends on firm and industry characteristics.

In the next section, we attempt to gain new insights into this question by deriving several theoretical hypotheses how the adoption of AM technology influences the likelihood that firms co-locate production and consumption around the globe and how a firm’s market scope impacts this relation.

3 Hypothesis building

3.1 Building blocks

To study these relations, we first need to clarify the concept of AM and provides some background on its origins and applications. AM or 3D printing is the collective term for all technologies making use of a layer-by-layer additive methods to construct three-dimensional solid objects in any shape from digital designs (Hannibal & Knight, 2018; Laplume et al., 2016; Rehnberg & Ponte, 2018). In contrast to traditional manufacturing, products are produced as a whole, circumventing the assembly of components (European Patent Office, 2017). AM brings together different older technologies such as

Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), laser and electron energy beam technology and machining/laser scanning (European Patent Office, 2017). While in mainstream language both AM and 3D printing are often treated as synonyms, there are minor differences as AM is a broader term. However, in this paper both terms will be used interchangeably, referring to the industrial application of these technologies.

For the past decade AM has been rapidly moving beyond its early role as a supporting activity through rapid prototyping to a main technology for manufacturing activities (Ahi, Sinkovics, Shildibekov, Sinkovics, & Mehandjiev, 2021; European Patent Office, 2017; Laplume et al., 2016). After reaching a global market volume of more than eight billion US dollars in 2016 with double-digit growth rates, the expectation is that the industry will grow to 21 billion US dollars by 2021 (Citi GPS, 2017). Although AM technologies were already introduced in the early 1980s, the current steady growth in patent applications only started in the early 2000s, when the technology proved to be useful for more than engineers only (European Patent Office, 2017; Lipson & Kurman, 2013). Between 2011 and 2015 the amount of 3D-related patent applications at the EPO more than doubled, reaching more than 500 applications in 2015. Since then, the number of distinct DOCDB patent families (measured across more than 90 of the most relevant patent offices around the world) has seen a steady rise over the past few decades with an exponential increase in more recent times, a trend which is expected to continue (European Patent Office, 2020a, 2020b).

Scholars have identified several ways how AM is transforming traditional production processes. First, like other digital technologies, AM reduces complexity by **facilitating the separability of design and manufacturing** and by allowing the interface between the two to be codified (Rehnberg & Ponte, 2018; Savolainen & Collan, 2020). Indeed, digital designs in the 3D printing technology can be easily transferred digitally and altered in geographically dispersed locations.

Second, AM leads to **shortened manufacturing supply chains**. AM technology has the capability to manufacture whole physical objects directly from raw materials, leapfrogging intermediate products

completely (Laplume et al., 2016). As Lim and Nair (2017) suggest: “With 3D printing, what would have initially been a series of stages of production could be cut down to a designer at one end, and the printer or “manufacturer” at the other. The middle players would most likely be suppliers of raw materials or “ink”. This is because several manufacturing and assembly steps are combined when using AM (Strange & Zucchella, 2017), hence the importance of traditional suppliers is likely to decline for firms making use of these production technologies. Buonafede et al. (2018), in their country- and sector-level research on AM, claim that this technology might decrease firms’ reliance on intermediates processed abroad and find evidence for this statement in the fabricated metal products, machineries and equipment industries.

Third, AM brings about **decreased economies of scale in plant-level manufacturing** (Ben-Ner & Siemsen, 2017). Whereas conventional specialized manufacturing technologies require the production of many units to justify the costs, AM allows the creation of very small and diversified batches at lower marginal costs through its low minimal efficient scale relative to conventional production (Hannibal, 2020; Laplume et al., 2016; Strange & Zucchella, 2017). This is because, unlike conventional manufacturing processes where costs are largely shaped by tooling expenses that are amortized over production runs, 3D printers have no fixed cost for product-specialized tools and molds (Atzeni & Salmi, 2012; Ben-Ner & Siemsen, 2017; Ruffo & Hague, 2007). Hence, these technologies may disrupt traditional manufacturing, replacing economies of scale with economies-of-one (Petrick & Simpson, 2013): flexibility, speed and complexity-for-free, typical of AM, allow to provide custom-made products with constant unitary costs.

Fourth, AM leads to **increased scale economies in R&D related to product design**. Product design is a textbook intangible asset that is non-rival in consumption (Mudambi, 2008; Teece, 2000): one individual or plant’s use of a product design does not subtract from the ability of others to use the same product design (Haskel & Westlake, 2017). This implies that their production generally involves

high fixed costs and low marginal costs, making them more scalable as their network use expands (Haskel & Westlake, 2017).

3.2 Sales and production co-location

This section covers the possible effects in terms of production in closer proximity to end-consumers (measured as the co-location of production and sales activities). The expected increase in co-location of production and sales activities driven by AM implementation is built on multiple expectations.

Plant scale economies. For starters, the opportunities offered by AM regarding decentralized production facilitate the relocation of production activities closer to customers (and thus sales subsidiaries) in order to regain flexibility which was lost through global production networks (Laplume et al., 2016; Strange & Zucchella, 2017). After all, since the early days of the industrial revolution the search for plant-level scale economies has been a serious constraint on the attractivity of production in close proximity to end-consumers, especially when these are located abroad (Laplume et al., 2016; Buonafede et al., 2018). Furthermore, 3D printing allows for easy factory replication, while ensuring consistent product quality (Bolwijn, Casella, & Zhan, 2018) and this advanced ICT application reduces the need for co-location with R&D or headquarters (where knowledge is created) (Alcácer, Cantwell, & Piscitello, 2016). According to Markusen's Knowledge-Capital model, the fact that AM technologies reduce the importance of plant-level scale economies sets in motion centripetal forces that make decentralized production in proximity to end-consumers more cost efficient than centralized production in a single country. In other words, companies that adopt AM technology are likely to move away from single-plant production in a single country towards multi-plant production across several markets with large concentrations of consumers, leading to an increased co-location of production and sales activities.

Relative endowments. A second factor contributing to the co-location of production and sales is related to AM's ability to reduce the importance of labor costs in the production process. Given the fact that worldwide the capital-cost differentials are very small in comparison to the prevailing labor-

cost differentials (Laplume et al., 2016), for SMEs with AM technologies, factor costs are of lower importance in the production location choice, offering more freedom in this respect. Companies are expected to base their location decisions less on production costs and more on proximity to customers after implementing AM technologies (Strange & Zucchella, 2017). According to Markusen's Knowledge-Capital model, the fact that the importance of differences in relative endowments declines when AM technologies is adopted reduces the incentive for companies to concentrate production in a single country. The combination of AM's high capital-intensity and the general capital cost convergence across countries pulls in the direction of more dispersed GVC configurations with more local production, leading to new opportunities to co-locate production and consumption (Laplume et al., 2016).

To summarize, the expectation of production in closer proximity to end-consumers for companies with AM capabilities is driven by diminished plant-level scale economies and a reduced importance of relative endowment differentials. This leads to our first hypothesis.

Hypothesis 1: *Firms with additive manufacturing capabilities are more likely to co-locate production and sales activities than firms without additive manufacturing capabilities.*

3.3 Moderating factor: Market scope

In this section, we bring in firm strategy by investigating if a firm's market scope influences the relation between AM technology adoption and the likelihood of production-consumption co-location. The main argument we propose is that companies which have invested more into catering to consumers in different market to take advantage of economies of scope are more prone to perform mass customization by co-locating production and consumption.

When internationalizing sales, the literature has identified and discussed two alternative strategies depending on the number of markets where a firm is looking to establish its presence: concentration and diversification (e.g., Ayal & Zif, 1979; Lee & Yang, 1990; Mas, Nicolau, & Ruiz, 2006), which are also

referred to as concentration and dispersion/spreading (e.g., Crick, Chaudhry, & Bastone, 2000; Katsikea, Theodosiou, Morgan, & Papavassiliou, 2005; Katsikeas & Leonidou, 1996; Piercy, 1981b).

There is a lack of consensus regarding the foreign-market expansion strategies a firm should adopt to improve its chances of success. One group of authors recommends the concentration strategy for foreign-expansion purposes (Bodur, 1994; Kahiya, 2018; Madsen, 1989). They argue that focusing on a relatively small number of key markets enables companies to secure a larger market share or achieve a high level of penetration—which, in turn, is associated with greater long-term profits—to reduce the administrative and transaction costs to avoid the dispersion of their marketing efforts and assign resources efficiently, and to pave the way for more in-depth knowledge of the specific characteristics of their chosen markets and the consumers who are part of them.

In contrast, other authors (e.g., Aulakh et al., 2000; Beamish et al., 1993; Lee & Yang, 1990; Piercy, 1981a, 1981b) advocate a market diversification strategy. They argue that international expansion into multiple markets, which involves small shares of highly dispersed markets, may reduce the risk of foreign operations as a result of the diversification of investments, result in greater market coverage, allow firms' greater operational flexibility because it is less dependent on just one or several markets, and enable organizations to achieve their desired level of international growth, which is more beneficial than concentrating on a small number of key markets.

Although studies indicate that firms pursuing market diversification strategies are more successful, the results might be driven by contextual factors as well as survival bias as market diversification strategies entail a higher risk (Sleuwaegen & Onkelincx, 2014). As such, a third group of authors (e.g., Aulakh et al., 2000; Ayal & Zif, 1979; Brouthers & Nakos, 2005; Katsikea et al., 2005; Madsen, 1989; Piercy, 1981b; Sleuwaegen & Onkelincx, 2014) argues that the suitability of a given market expansion strategy depends on various situational factors, such as the specific characteristics of the firm, the product, and the industry involved (Piercy, 1981b).

Research has clearly shown that product level adaptation to the various market differences favors the rapid expansion to larger number of foreign markets. Some products have a high customization requirement as they necessitate adaptation of a product to suit individual customers. Such an expansion is further stipulated by the innovativeness of new products, which require careful adaptation (Kyriakou & Tsogas, 2022).

It can also help create additional value through economies of scope in operating in multiple countries (Aulakh et al., 2000; Reid, 1981). In particular, firms can increase the sales of their products and services by targeting similar customer segments across countries. This market scope advantage is particularly strong for firms that tend to follow niche strategies (Ebben & Johnson, 2005). As Aulakh et al. (2000) explain, when following a niche strategy "the potential market in any one country is saturated very quickly, and the only way to expand the size of the market is to target like segments in different countries". Spreading the market scope can also serve as a hedging mechanism against uncertainty and risk in the firm's internationalization efforts (Patel et al., 2018).

When applied to our context, on-demand production in distributed locations represents one scenario in which AM can enable a redesign of the supply chain to better meet customers' needs. In this scenario, a decentralized network of 3D printers replaces some or all of the centralized production facilities that use conventional equipment (Deloitte, 2015). It stands to reason that AM provides a possible vehicle to product adaptation and customization and greatly reduces the time from production to utilization. As AM can produce a wide range of products without retooling or reconfiguration (Laplume, Petersen, & Pearce, 2016), it can be especially well suited for tasks of customization. Furthermore, even these highly digital connections require the direct personal exchanges for technology potential learning among firms in geographic proximity. Digital technologies cannot fully substitute personal contact, which are also required to keep friend- and relationships alive (Bouncken et al., 2023).

Unbundling of certain high knowledge activities may no longer be needed or even possible, as R&D, innovation, design and branding are intensely related to manufacturing of physical products. Co-location synergies of these activities may be so high that it is not wise to produce in a dispersed manner (Ketokivi & Ali-Yrkkö, 2009; Tassey, 2014). As a result of this decentralization trend, AM offers the ability to co-locate and thereby integrate design with manufacturing (Brennan, et al., 2015).

A diversification strategy has also been suggested as one of the dominant reasons for internalization (Denis, Denis, & Yost, 2002; Markides & Ittner, 1994). It is argued international investments abroad not only provide access to important resources including customer access and feedback, but also allow firms an opportunity to reduce the costs and risks of entering into new foreign markets (Boateng & Glaister, 2003; Cos, Colom & Cabasés, 2019).This internalization has also been strengthened by the technological intensity of the product, increasing the need for technology protection (Buckley & Casson, 1976). Due to the non-excludability property of design knowledge, an AM firm does not want to reveal its technology to an external company. After all, the external firm could reject a deal and go and copy the technology at little cost. AM firms therefore have a heightened incentive to internalize their production to circumvent these knowledge appropriability hazards (De Beule et al., 2022).

In sum, additive manufacturers that follow a market diversification strategy through a trend towards mass customization (D'Aveni, 2013) are more likely to co-locate production with sales. As such, co-location would seem to be dependent upon the market scope of the firm. These ideas motivate that products that involve high customization requirements will be positively associated with greater localization of production. Local adaption would enhance value to the end-user at a very low cost for re-tooling, and tend to encourage local production for firms that follow a market spreading internationalization process. This decentralized market scope, in turn, would lead to an impetus for co-location of production and sales.

Hypothesis 2: *Additive manufacturers that pursue market diversification are more likely to co-locate production and sales activities than additive manufacturers that do not pursue market diversification.*

4 Data and methodology

To study the relation between AM and the likelihood that a firm will co-locate production and sales, we have collected information on the production and sales subsidiaries of all additive manufacturers and compared their international production co-location to a sample of comparable non-additive manufacturers.

In order to construct this dataset, we have used Bureau Van Dijk's ORBIS database as well as the European Patent Office's PATSTAT database. The ORBIS database has been used to collect company financial and investment information to determine international manufacturing investments while the PATSTAT database has been used to collect patent information to determine those firms that have additive manufacturing capabilities.

ORBIS contains financial, legal and ownership data on more than 375 million private and public companies around the world (Bureau van Dijk, 2020) and has often been used in IB research to analyze internationalization and location decisions (Alon, Elia & Li, 2020; Elia, Kafouros & Buckley, 2020; Pla-Barber, Botella-Andreu, & Villar, 2021). To be included in our final dataset, companies have to meet four conditions. First, companies have to be Global Ultimate Owner (GUO) of their corporate group, which in this paper is defined as industrial companies (i.e. no individuals, governments, universities, research foundations, holding companies, financial or insurance institutions) with a minimum 25% of total control over their subsidiaries, without being controlled themselves. Second, given that we want to focus on additive manufacturing, we have opted to analyze firms that have been set up since 2000. The selection of this starting year has been informed by the commercialization of AM around this point in time (EPO, 2017: p. 53). Third, we have selected small, medium, and large firms but have excluded very large firms regardless of their use of AM technology as the impact cannot be separated given their size. To develop a comparable dataset across countries, we have used information from Bureau Van Dijk (2020) to exclude firms with more than one thousand employees in combination with an operating revenue of more than € 100 million and total assets of more than € 200 million. Finally, the company

has to carry out manufacturing activities, defined as having assigned one or multiple primary or secondary industry codes in the field of manufacturing (NACE codes 10 through 33, see further). In total, about 4 million companies satisfy these criteria and make up the full dataset employed in this paper although also smaller, more comparable subsamples have been employed for the econometric analyses. All foreign subsidiary ownership data (if any) for these companies are used to construct all corporate group members.

To identify companies with AM capabilities (AM firms), we rely on the European Patent Office's PATSTAT database, which contains more than 100 million patent documents from more than 90 relevant patent authorities around the world. PATSTAT Autumn 2019 edition is utilized, which contains up to date patent information until June 2018. Three steps are followed in determining additive manufacturing firms. First, to identify patents that can be linked to AM capabilities, we build upon existing studies (D'Appolonia, 2014; De Beule, Van Assche, & Nevens, 2022; EPO, 2017; Hidemichi & Shunsuke, 2018; Huang, 2016; Salvador, et al., 2015; Yegros et al., 2018) to come to a comprehensive list of AM-related Cooperative Patent Classification (CPC) codes. This list includes CPC codes that have been established more recently as a result of the advent of AM, as well as CPC codes that were used previously to register AM patents by patent examiners. In a second step, all AM-related patent applications are identified, with the help of a search query containing all AM-related CPC codes (see Appendix 1). In total, the PATSTAT Autumn 2019 database renders 221,928 AM related patents. In a third step, all patents are matched to the GUOs and their subsidiaries using the patent applicant on the patent, following a name disambiguation and harmonization procedure. To associate these patents to the GUOs of the corporate groups from the ORBIS database (see previous step), all patents are linked to applicant firms and consolidated on a group level. This consolidation is needed given that firms sometimes decide to register patents using different applicant firms because of strategic or fiscal reasons (Baumann, Böhm, Knoll, & Riedel, 2020; Gaessler, Hall, & Harhoff, 2021). After consolidating the patent data to the GUO-level, it is possible to identify all GUOs that have AM capabilities. This matching procedure allows us to match AM patents to 3,608 GUOs (and their subsidiaries) in ORBIS.

However, as not all firms report relevant financial and ownership data of subsidiaries, the final dataset includes 560 GUOs of corporate companies with AM capabilities, that is, AM firms.

4.1 Variables & statistical techniques

4.1.1 Dependent and independent variables

The dependent variable is a count variable measuring the extent of production and sales co-locations (**GUO_tot_manuf_sales_coloc**). This variable has been constructed by analyzing the activity codes of all foreign subsidiaries. If a subsidiary reports at least one primary or secondary NACE activity codes in the field of manufacturing as well as sales, it is considered as a subsidiary with co-located production and sales. The dependent variable has been constructed by summing the number of foreign co-locations per global ultimate owner (GUO).

The two independent variables of interest for our hypotheses is a variable measuring whether a firm is an additive manufacturer, on the one hand, and the extent of international market diversification, on the other hand. This is done through an AM-patent dummy (**GUO_3DP**) that takes on the value of 1 if the GUO has filed at least one patent application related to AM, and 0 otherwise. We will also use the number of AM patents in our robustness checks. Following extant research, international market diversification has been measured as the number of foreign countries where the company has set up a sales subsidiary (**GUO_tot_foreign_subs_countries**). In order to measure the moderating effect of international market diversification on co-location, comparing additive with non-additive manufacturers, the market diversification will be interacted with the additive manufacturing dummy.

4.1.2 Control variables

Several control variables are included which are traditionally used in studies on firm internationalization. The first control variable is a count variable measuring the age of the companies (in years since incorporation) (**AGE**). This is important to include as the older firms are, the more likely they have had time to develop capabilities that help them in the internationalization process although

others contend that age can become a break on the speed of internationalization because of behavioral lock-in. Despite the opposing arguments in international entrepreneurship research on born globals and international new ventures, age has been widely shown to have an important and significant relation with venture internationalization (Acedo, Coviello & Agusti, 2021; Meschi, Ricard & Moore, 2017; Simón-Moya, Revuelto-Taboada, & Ribeiro-Soriana, 2012).

Second, firm size is included in the shape of a normalized (z-score) index variable which combines the number of employees, operating revenue and total assets in one measure (**SIZE**). Previous research has established a significant positive relationship between firm size and internationalization (Simón-Moya, Revuelto-Taboada, & Ribeiro-Soriana, 2012). Size has been shown to be an important indicator for international activity, mainly as a proxy for managerial competences and financial resources (Giovannetti, Marvasi & Sanfilippo, 2015; Haddoud, Onjewu, Nowinski & Jones, 2021; Martineau & Pastoriza, 2016).

As the diffusion of additive manufacturing technologies and its subsequent effect on firm's international production structures is likely to vary across industries (Laplume et al., 2016; Rehnberg & Ponte, 2018), a third control variable of interest is the industry in which the (non-)additive manufacturers are active. Based on previous literature, this paper makes a distinction between four industry groups (operationalized with the help of three industry group dummies), as can be seen in Appendix 2. First, there are some heavily affected industries in which the implementation of additive manufacturing technologies is already widely implemented (industry group dummy **NACE_HAI**). In most of the cases these involve small products made of just one material without many interacting parts (e.g. jewelry, music instruments, sports goods and toys, medical instruments) (Laplume et al., 2016; Hannibal & Knight, 2018). To a large extent this involves the manufacturing of rubber and plastics products, as well as the manufacturing of non-metallic mineral products (NACE codes 22 and 23). Furthermore, 3D printing is well established for equipment replacement parts (NACE code 33), as these

parts tend to be very unique and complex to create using traditional manufacturing techniques (Laplume et al., 2016).

Adding to this, there is a plethora of industrial fields in which the implementation of AM technologies has taken place to a certain extent, but its full potential is yet to be realized, labelled the medium affected industries (industry group dummy **NACE_MAI**). Areas such as computer and electronics manufacturing (NACE code 26), electrical equipment manufacturing (NACE code 27), automotive (NACE code 29) or aerospace (NACE code 30), where AM is mainly used to prototype or manufacture intermediary components with complex geometric features belong to this second category (Gambell et al., 2017). Moreover, thanks to significant increases in the development of printable clays and ceramics for medical applications (e.g. prosthetics, orthopedic implants, dental implants or hearing aids) AM's use is expanded in the health care industry (NACE code 21) as well (Laplume et al., 2016). The wearing apparel industry (NACE code 14) concludes the medium affected industries in this paper as the role of AM here is restricted to specialized fashion with complex geometries (Laplume et al., 2016).

In addition, there are several industries unlikely to be highly affected by AM technologies, now or in the future. These industries involve products made of natural materials (e.g. wood, cork, leather, paper) as 3D printing would abolish the desirable natural properties of these materials. Furthermore, the production of industrial raw materials is unsuitable for AM because these products cannot be printed (Laplume et al., 2016). Consequently, industries with the following NACE codes are unlikely to be strongly affected by AM implementation: 10, 11, 12, 13, 15, 16, 17, 19, 20 and 24. These industries make up the base group in this research and the dummy is therefore not included as a variable in the regressions because of the dummy variable trap.

Finally, the manufacturing of machinery and equipment n.e.c. (NACE code 28), in which the production of AM machinery is included, is taken up as industry group dummy **NACE_PAM**. As these machines are not produced using AM themselves, the consequences of having AM knowledge on the international

production structure is not likely to have a similar impact than other additive manufacturers, so is likely to be smaller in this industry. However, these companies could potentially also set up production facilities of their 3D printers to be able to supply 3D printing services to other companies wishing to take advantage of the new technology for some of their production or products.

In summary, the expectation is that the impact for AM firms in heavily or medium affected industries will be more pronounced than for the other industries. Companies in heavy or medium affected industries are far more likely to use AM as a substitute, rather than as a complement to traditional production methods (Rehnberg & Ponte, 2018). When AM is used as a complement (e.g. for prototyping), effects on the geographical dispersion of production are expected to be relatively small, however when AM is used as a substitute for traditional production (in industries where this is both technologically and economically feasible), the technology tends to induce small-scale, dispersed, localized production in closer proximity to end consumers (Laplume et al., 2016; Rehnberg & Ponte, 2018).

Furthermore, research has shown that there are also country-level factors that determine internationalization. The market size of the home country should therefore be taken into consideration as companies that have their headquarters in relatively large countries are probably less likely to internationalize their production activities because they already have a large domestic market and do not necessarily need to internationalize production in order to scale. A dummy variable measuring the home country size of the companies is included, measured by the Gross Domestic Product of the home country. This dummy takes on value 1 if the company's home country belongs to the top countries in terms of their GDP as of 2018 (United States, China, Japan, Germany, India, United Kingdom, France, Italy, Brazil, Canada, Russia, South Korea, Spain and Australia) and value 0 otherwise (**GDP_L**).

Finally, more innovative firms have been shown to internationalize production more because they are more likely to have competitive advantages that they want to leverage abroad. This has been measured by the ownership of patents. Although this is an output measure of innovation, research has

shown that there is a very large statistical overlap between the various indicators of innovation, i.e., R&D expenses, patent counts, patent citations and new product announcements such that research can essentially use any of these indicators individually to measure the innovative performance of firms (Brem & Nylund, 2021; De Beule & Van Beveren, 2012; Hagedoorn & Cloodt, 2003; Deng et al., 2014). An innovation dummy variable is therefore included taking on value 1 if a company is the owner of at least one patent and value 0 otherwise (**INNO**). We have also used the number of patent publications (**GUO_log_pub**) rather than a dummy.

The correlation table for all variables has been included in Appendix 3. None of the independent and control variables demonstrate problematic multicollinearity. In summary, this leads to the following model specification:

$$International\ production\ and\ sales\ co-location_i = \beta_0 + \beta_1\ 3DP_i + \beta_2 SIZE_i + \beta_3\ AGE_i + \beta_4\ NACE_MAI_i + \beta_5\ NACE_HAI_i + \beta_6\ NACE_PAM_i + \beta_7\ GDP_L_i + \beta_8\ INNO_i + \varepsilon_i\ , for\ each\ company\ i.$$

4.1.3 Statistical models

In order to estimate the relation between AM and the co-location of international production and sales, two different statistical models are used. First of all, due to the large size of the dataset (more than 4 million observations) and the relatively small number of AM-companies (560), propensity score matching (PSM) is used. PSM estimates the effect of a treatment (having AM capabilities, in this case) by comparing the treated cases with a purposefully established control group of non-treated who have similar characteristics as the treated group. This allows for an analysis of additive manufacturers to a smaller set of comparable non-additive manufacturers. Following the literature review, the propensity scores are in a first step calculated making use of firms whose **AGE**, **SIZE** and industries (**NACE_MAI**, **NACE_HAI** and **NACE_PAM**) are similar, only taking into consideration cases with similar propensity scores to the treated (common support option), and stratifying cases into blocks according to their propensity scores. In a second step, the average treatment effects on the treated firms are calculated

making use of both nearest neighbor matching and stratification matching. While in the stratification matching all firms are still taken up in the analysis, nearest neighbor matching only compares the additive manufacturers to similar non-additive manufacturers. While PSM is a highly recommended econometric analysis for hypothesis 1, it does not allow for interaction variables in the treatment. Besides, it gives statistical evidence about the relation between AM capabilities and the dependent variable without providing information on the effects of the control variables.

The second statistical model employed in this paper is the zero-inflated negative binomial model (ZINB) This model is specifically designed to work with the count values of the dependent variable given that OLS regression techniques would not give consistent estimators. The ZINB model is designed to work with count data and solves two issues with the nature of the dependent variable (**GUO_tot_manuf_sales_coloc**). The first issue is related to the equidispersion (mean more or less equal to variance) assumed by other statistical methods, which is not the case for our dependent variable (see Table 1). The negative binomial model takes into account this overdispersion by adding a parameter reflecting unobserved heterogeneity among observations as a random variable, allowing for more variance.

The second issue is related to the fact that the dependent variable has a lot more observed zeros than standard models would be able to predict. The zero-inflated model takes care of this excess of zeros and is built on the logic that a zero outcome can be due to two different processes, and consequently has two equations. One equation checks the probability of a firm having no foreign co-located subsidiaries and is parametrized by a probit in this paper. The second equation of interest is a negative binomial regression for the group of firms who do not belong to the 'always zero' foreign co-located subsidiaries and can be used to test our hypotheses. This part of the ZINB regression therefore only compares firms that have already internationalized, avoiding a comparison of firms that have internationalized with firms that have not.

In summary, both statistical models will allow us to compare the 560 additive manufacturing companies in our sample to comparable non-additive manufacturers, albeit in different ways. Both models will be applied to the entire sample as well as a smaller sample of non-additive manufacturers that can be matched on relevant characteristics to analyze the impact of additive manufacturing in terms of co-location of sales and production.

5 Results

5.1 Descriptive statistics

Table 1 provides an overview of all the relevant dependent and control variables, over both groups of companies (AM versus non-AM firms). Significant differences can be observed between both groups concerning their internationalization and co-location of production and sales. Additive manufacturers (3DP=1) are on average present in 10 times as many countries (**Tot_foreign_countries**) as non-additive manufacturers. Non-additive manufacturers are also 6 times less likely to co-locate production with sales activities. This is also nicely illustrated by the maximum observation where a non-additive manufacturer is present in 79 countries but only produces in 15 while the top additive manufacturer is present in 39 countries but also manufactures in 26 of those countries.

AM companies are on average also slightly older than non-additive manufacturers (**AGE**) (9 versus 8 years), have more employees (**SIZE**) (51 versus 11), have a larger operating revenue (7.5 million versus 1 million euros) and have bigger total assets (13 million versus 1.7 million euros). The majority of non-AM companies is small according to Bureau van Dijk's (2020) definition (82.91%), whereas 14.70% has a medium size and only 2.38% is large. For AM companies a different distribution can be observed with 47.50% small, 35% medium sized and 17.50% large companies.

Concerning the industry groups in which the companies in the dataset are active (see Appendix 2), some differences can be observed between the companies without and with AM capabilities. For the former group 29.08% are active in so-called unaffected industries (**NACE_UI**), 41.93% in the medium

affected industries (**NACE_MAI**), 23.50% in the highly affected industries (**NACE_HAI**) and 5.49% in industries related to the production of AM machinery (**NACE_PAM**). As expected, AM firms are less active in unaffected industries (10.89%) and more active in industries related to the production of AM machinery (19.82%), while the distribution in medium (42.86%) and highly affected industries (26.43%) is similar to the companies without AM capabilities.

Table 1. Descriptive statistics for relevant dependent, independent and control variables between comparable additive and non-additive manufacturers.

		Mean		St. Dev.		Maximum	
		3DP = 0	**3DP = 1**	**3DP = 0**	**3DP = 1**	**3DP = 0**	**3DP = 1**
Tot_manuf_sales_co		0.0133	0.0839	0.21038	1.11828	15	26
Tot_foreign_countries		0.0209	0.2314	0.51145	1.85803	79	39
AGE		7.9526	9.0929	5.0796	5.0531	18	18
SIZE	**Employees**	10.7013	50.7541	39.5884	101.4495	999	740
	Revenue	1,074,418	7,521,901	4,836,089	15,556,348	99,971,529	93,398,780
	Total Assets	1,744,633	12,955,008	7,121,241	26,013,414	199,476,580	188,516,790

Furthermore, an analysis of the home country of the companies in the dataset shows that 20.54% of AM firms is Chinese (as compared to 13.86% of the companies without AM knowledge), 10.71% is German (while only 1.45% of the control group is), 14.11% is South Korean (as compared to 2.38% for the non-AM firms) and 31.07% is from the USA (as compared to 9.47% for the control group). This also indicates the need for controlling for the home country in the regression as well as in the matching blocks for the propensity score matching.

For the group of non-AM firms 25.85% has its headquarters in smaller countries (**GDP_S**) (meaning in a country outside the top countries with the highest GDP), while 74.15% is based in larger countries (**GDP_L**). For AM firms, this distribution is respectively 11.61% and 88.39%. Finally, 1.66% of the companies in the group of non-AM capability owners has registered a patent (**INNO)**.

5.2 Econometric results

First, in order to confirm our first hypothesis, we used propensity score matching. We used two different econometric models, nearest neighbor matching as well as the stratification method, to calculate the treatment effect, which refers to the use of additive manufacturing in a firm.

In a first step, PSM based on company age, size, industry group and home country is used to match the non-AM firms which are most similar to the AM firms. This has been done to control for the differences in both subsamples as discussed in the description of the sample. In a second step, the average treatment effect (ATT, with the treatment being 3DP) concerning the foreign production subsidiary dummy is calculated making use of two distinct methods (nearest neighbor matching and stratification), both with company age (AGE), size (SIZE) and industry groups (NACE_MAI, NACE_HAI and NACE_PAM) as well as the home country size (GDP_L) as matching variables. This is basically applying the following model specification to calculate the average treatment effect:

$$ATT = E(Y_1\text{-}Y_0 \mid T = 1),\ \textit{with Treatment T being an additive manufacturer, after matching for a set of variables X (AGE, SIZE, INDUSTRY and HOME COUNTRY).}$$

As can be seen in Table 2, a significant positive relation between AM firms and the propensity to co-locate foreign production and sales activities can be observed for both models (nearest neighbor matching and stratification). The stratification method uses the full sample of non-additive manufacturers to compare to additive manufacturers, while the nearest neighbor method only uses firms that are similar to their additive competitors. While the nearest neighbor matching method is arguably a more relevant comparison, both results indicate that AM firms have a significantly higher probability of co-locating foreign production subsidiaries with sales subsidiaries than non-AM firms.

Table 2. Results average treatment effects (3DP) through propensity score matching for co-location of foreign production and sales.

Number of treated	**Number of control firms**	**Average treatment effect**	**Robust Standard Error**	**p-value**
Hypothesis 1: Effect of 3DP on foreign production subsidiary dummy (FPS_d)				
Nearest neighbor matching method				
560	32,861	0.071**	0.047	0.000
Stratification method				
560	3,981,685	0.079**	0.047	0.000

Table 3. Tobit regression results for full sample of firms and comparable innovative firms

	(1)	(2)	(3)	(4)	(5)	(6)
GUO_Z_SIZE	0.00156***	0.00696***	0.00156***	0.00707***	0.00138***	0.00450***
	(0.0000493)	(0.000999)	(0.0000493)	(0.000999)	(0.0000470)	(0.000851)
GUO_AGE	0.000142***	-0.000362*	0.000143***	-0.000299	0.000148***	-0.000221
	(0.00000801)	(0.000204)	(0.00000801)	(0.000204)	(0.00000764)	(0.000174)
GUO_NACE_MAI	-0.000561***	-0.0126***	-0.000560***	-0.0126***	-0.000478***	-0.00970***
	(0.0000928)	(0.00260)	(0.0000928)	(0.00260)	(0.0000885)	(0.00221)
GUO_NACE_HAI	-0.000516***	-0.00758**	-0.000519***	-0.00784**	-0.000473***	-0.00638**
	(0.000107)	(0.00305)	(0.000107)	(0.00305)	(0.000102)	(0.00260)
GUO_NACE_PAM	0.000483***	-0.0129***	0.000482***	-0.0131***	0.000480***	-0.0122***
	(0.000180)	(0.00313)	(0.000180)	(0.00313)	(0.000172)	(0.00267)
GUO_ISO_GDP_L	0.00142***	-0.0118***	0.00143***	-0.0117***	0.00174***	0.00459*
	(0.0000884)	(0.00283)	(0.0000884)	(0.00283)	(0.0000843)	(0.00241)
GUO_log_pub	0.00774***	0.0112***	0.00734***	0.0106***	0.00311***	0.00388***
	(0.000161)	(0.000905)	(0.000163)	(0.000912)	(0.000156)	(0.000778)
GUO_3DP			0.0592***	0.0569***	-0.0547***	-0.0572***
			(0.00330)	(0.00997)	(0.00317)	(0.00855)
GUO_tot_foreign_subs_countries					0.208***	0.157***
					(0.000384)	(0.00151)
GUO_3DP* GUO_tot_foreign_subs_countries					0.336***	0.386***
					(0.00172)	(0.00476)
_cons	0.000146	0.0145***	0.000139	0.0141***	-0.000246**	0.00653*
	(0.000116)	(0.00404)	(0.000116)	(0.00404)	(0.000110)	(0.00344)
/ var(e.GUO_tot_manuf_sales_coloc)	0.00597***	0.0542***	0.00597***	0.0542***	0.00544***	0.0393***
	(0.00000420)	(0.000297)	(0.00000420)	(0.000297)	(0.00000382)	(0.000215)
N	4049526	66654	4049526	66654	4049526	66654

Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Second, ZINB regressions were applied to two samples of firms. The first sample is the full sample and includes more than 4 million firms. The second sample is the reduced sample of innovative firms and includes more than 66 thousand firms. While the reduced sample of firms is arguably more comparable in terms of comparing innovative firms, both models always confirm the same result. The results indicate that while additive manufacturers are more likely to co-locate production with sales (see Models 3 and 4), this result is entirely driven by market diversification as the coefficient for the direct effect of additive manufacturing (GUO_3DP) turns negative for Models 5 and 6. However, the interaction variable more than compensates for this negative coefficient, meaning that co-location is very much driven by market diversification through the number of sales markets where the firm is operating.

So while the direct model indicates that additive manufacturers are more likely to co-locate manufacturing and sales, the moderation model clarifies that this increased co-location is only the case if additive manufacturers need to customize products to the local sales market.

6 Discussion and conclusion

Digital technologies are changing the nature and scale of investment projects across the globe. Additive manufacturing, in particular, has been touted to induce a shift away from large-scale manufacturing projects towards smaller manufacturing facilities closer to key markets.

Although some have indeed predicted that “In 2030, across all industries local production near customers enabled by additive manufacturing will increase significantly whereas globally spread production chains will decrease, resulting in a de-globalization of supply chains” (Jiang, Kleer, & Piller, 2017), our results indicate that we need to qualify this statement. Our results indicate that this prediction depends highly on the product: for standardized products, centralization makes more sense, meaning that additive manufacturers might have centralized printing facilities rather than decentralized operations. To give an example, while printing shoes might be done on the spot, fitting

to a customers' feet, printing automotive spare parts might be done in a more centralized or regionalized production facility rather than at the point of replacement. Furthermore, mass-produced parts and materials will remain globally produced but customized production, and instances where sustainable production is demanded, will occur more locally (Jiang, Kleer, & Piller, 2017). The need for product customization and quick responsiveness to changing customer preferences therefore might explain the extent of diffusion and internationalization of 3D printing technology in a given industry (Laplume, Petersen, & Pearce, 2016). There is an increasing need for personalized customization and customers want their products quicker and quicker, inducing an increased need for customer proximity. In the event customization needs increase over time, local production likely would rise (Laplume et al., 2016) and production can move back to where consumption is (Garrett, 2014).

This has impacted key manufacturing locations in emerging economies that have previously benefitted from their role as export platforms. 3D printers are widely used and further technological progress in 3D printing leads to a gradual replacement of international trade by local production (Abeliansky, Martinez-Zarzoso, & Prettner, 2016).

As such, additive manufacturing will favor more decentralized production and distribution (Scalabre, 2016), suggesting that the new manufacturing will become more productive and flexible, with several implications:

On the one hand, this could favor the relocation of factories in home countries, or imply that the decisions regarding localization may be influenced by a "consumer proximity" logic. For instance, back- or nearshoring to North-America and Europe can happen, since they are dominating in installed capacity and demand for 3D printers (Rehnberg & Ponte, 2018). AM can support backshoring because it provides a higher productivity and flexibility which offers an incentive for firms to locate production close to their European customers (Dachs, Kinkel, & Jäger, 2017). If AM would substitute traditional manufacturing, decentralization and location with production moving closer to the customer is likely.

On the other hand, this revolution will affect the size of factories, which will become smaller, agile, flexible, multiproduct, and adopting a make-to-order logic (Chiarvesio & Romanello, 2018). This is already happening (FabLab movement, 3DHubs) and will steadily increase due to the need for customized and sustainable production (Jiang, Kleer, & Piller, 2017). In those industries and industry segments where 3D printing is both technologically and economically feasible, and the technology diffusion accordingly high, the technology tends to induce small-scale and local production (Laplume, Petersen, & Pearce, 2016).

Fabricating objects at or near the point of use reduces the inventories required to support customer availability expectations, significantly reduces lead time, and reduces dependency on forecast accuracy. These benefits arise because the distributed production on demand supply chain is flexible enough to respond to unpredictable customer demand without incurring additional costs, such as transportation, customs, taxes, and other costs associated with logistics (Holstrom et al., 2010). Once 3D printing becomes widely applicable and economically viable for mass production it will boost 'local for local' production with 3D printers at the expense of imports (ING, 2017).

Before drawing a conclusion, it is important to indicate several limitations to our study. First, although we have used a novel approach to develop the population of additive manufacturing companies, the use of patents to derive whether a firm is an additive manufacturer or not, is not without flaws. Specifically, there might be some additive manufacturers that have not patented their knowledge and inventions, thus leading to an undercounting of additive manufacturers in our sample. Although research has shown that leading firms typically protect their knowledge through patenting (Chandrashekar & Bala Subrahmanya, 2019), we acknowledge that our process for identifying AM firms might be too restrictive in some instances. Having said that, we would argue that a more appropriate identification of AM firms (if possible) would only strengthen our results which currently are likely underestimated. There is nonetheless more quantitative research to be done that uses different

methods to identify firms which embrace fourth industrial revolution technologies such as additive manufacturing and that contrast their internationalization behavior with that of other firms.

Second, although our paper has controlled for differences across industries, there is obviously a lot more work to be done to identify in which industries additive manufacturing provide the biggest bang for its buck in terms of product internationalization. Relatedly, the impact of 3D printing companies on the rest of the industry is an appealing research avenue. Will it lead to the widespread introduction of decentralized availability of additive manufacturing capacity, which will drive production externalization, or is it more likely to lead to centralized 3D printing resources? This is most likely to depend on other factors, such as the industry, technology and materials, so requires much more research.

Third, our analysis has not focused on the specific location of internationalization of additive manufacturers. Although the literature review has shown that other drivers, such as skill availability and technological development, are more likely to have an impact on locations than labor costs, much work needs to be done to tease out the drivers and impact of these factors on firms and locations. In particular, the impact on developing and emerging economies might be a useful unit of analysis given that they risk losing out as a result of additive manufacturing, putting their industrialization and economic development at risk.

A fourth avenue of research has to do with the internationalization and co-location of other value chains, both upstream such as research and development and downstream such as sales. Given that AM technology makes it easier to separate design and production, this might lead to a reduction in the need for the internationalization of R&D, while production might be more linked to marketing and sales, allowing for more adaptation as a result of the specificities of decentralized flexibility of additive manufacturing.

In summary, additive manufacturing is changing the way we produce things. In particular, we show that additive manufacturers are more likely to co-locate production and sales activities than firms

without additive manufacturing capabilities if they are pursuing international market diversification. We provide new evidence that it has a major effect on companies' production, which requires us to rethink the global factory and global value chains (Buckley & Strange, 2015). This, in turn, is likely to also have a major impact on the host countries that aim to attract investment to their shores.

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APPENDIX

Appendix 1 - Cooperative Patent Classification (CPC) codes related to Additive Manufacturing

CPC code	Description
A61C 13/0013	Dental prostheses; Making same; using stereolithographic techniques
A61C 13/0019	Dental prostheses; Making same; using three dimensional printing
A61F 2002/30962	Prostheses implantable into the body; Joints; Designing or manufacturing processes; for designing or making customized prostheses; using stereolithography
A61F 2002/30985	Prostheses implantable into the body; Joints; Designing or manufacturing processes; for designing or making customized prostheses; using three dimensional printing
B22F 3/1055	Manufacture of work pieces or articles from metallic powder characterized by the manner of compacting or sintering; Apparatus specially adapted therefor ; Sintering only ; by using electric current ; Selective sintering, i.e. stereolithography
B29C 64	Additive manufacturing, i.e. manufacturing of three-dimensional objects by additive deposition, additive agglomeration or additive layering
B33Y	Additive manufacturing, i.e. manufacturing of three-dimensional objects by additive deposition, additive agglomeration or additive layering
C04B 2111/00181	Mortars, concrete or artificial stone or mixtures to prepare them, characterized by specific function, property or use; Physico-chemical characteristics of the mixtures; Mixtures specially adapted for three-dimensional printing, stereo-lithography or prototyping

C04B 2235/665	Aspects relating to ceramic starting mixtures or sintered ceramic products; Aspects relating to heat treatments of ceramic bodies such as green ceramics or pre-sintered ceramics ; Specific sintering techniques ; Aspects relating to heat treatments of ceramic bodies such as green ceramics or pre-sintered ceramics
G03F 7/70416	Photomechanical ; Exposure apparatus for microlithography ; Imaging systems not otherwise provided for ; Stereolithography, 3D printing, rapid prototyping
G05B 2219/49018	Program-control systems ; Nc systems ; Nc machine tool, till multiple ; Laser sintering of powder in layers, selective laser sintering SLS
Y02B 10/29	Technologies related to metal processing ; Process efficiency ; Additive manufacturing

Appendix 2 - Diffusion of AM technologies over NACE manufacturing industries (class C) (based on Laplume et al., 2016; Gambell et al., 2017; Hannibal & Knight, 2018)

Unaffected Industries		**Mildly Affected Industries**		**Heavily Affected Industries**	
10	Manufacturing of food products	**14**	Manufacturing of wearing apparel	**22**	Manufacturing of rubber and plastics products
11	Manufacturing of beverages	**18**	Printing and reproduction of recorded media	**23**	Manufacturing of other non-metallic mineral products
12	Manufacturing of tobacco products	**21**	Manufacturing of pharmaceuticals, medicinal chemicals	**32**	Other manufacturing
13	Manufacturing of textiles	**25**	Manufacturing of fabricated metal products	**33**	Repair and installation of machinery and equipment
15	Manufacturing of leather and related products	**26**	Manufacturing of computer, electronic and optical products		
16	Manufacturing of wood and cork products	**27**	Manufacturing of electrical equipment	**Production of AM-machinery**	
17	Manufacturing of paper products	**29**	Manufacturing of motor vehicles and (semi-)trailers	**28**	Manufacturing of machinery and equipment n.e.c.

19	Manufacturing of coke and refined petroleum products	**30**	Manufacturing of other transport equipment		
20	Manufacturing of chemicals and chemicals products	**31**	Manufacturing of furniture		
24	Manufacturing of basic metals				

Appendix 3. Pairwise correlation table

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) GUO_tot_manuf_sales_coloc	1.000									
(2) GUO_3DP	0.012*	1.000								
(3) GUO_tot_foreign_subs_countries	0.286*	0.028*	1.000							
(4) GUO_AGE	0.017*	0.003*	0.005*	1.000						
(5) GUO_Z_SIZE	0.024*	0.012*	0.012*	0.317*	1.000					
(6) GUO_NACE_MAI	-0.002*	0.000	-0.001	-0.007*	-0.006*	1.000				
(7) GUO_NACE_HAI	-0.002*	0.001	-0.001*	-0.036*	-0.038*	-0.471*	1.000			
(8) GUO_NACE_PAM	0.007*	0.007*	0.003*	0.101*	0.086*	-0.205*	-0.134*	1.000		
(9) GUO_ISO_GDP_L	0.011*	0.004*	-0.004*	0.004*	0.102*	0.004*	0.020*	0.038*	1.000	
(10) GUO_log_pub	0.027*	0.139*	0.048*	0.081*	0.132*	0.016*	-0.013*	0.057*	0.041*	1.000

*$p<0.05$