The impact of 3D printing on trade and FDI

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Abstract

This paper analyzes the effects of 3D printing technologies on the volume of trade and on the structure of FDI. A standard model with firm-specific heterogeneity generates three main predictions. First, the model predicts that 3D printers are introduced in areas with high economic activity and subject to high transport costs. Second, technological progress related to 3D printing machines leads to a gradual replacement of FDI that relies on traditional production structures with FDI based on 3D printing techniques. At this stage international trade stays unaffected. Finally, at later stages, with 3D printing machines being widely used, further technological progress in 3D printing leads to a gradual replacement of international trade. Empirical evidence indicates that countries subject to higher transport costs and with high levels of economic activity are indeed among the ones that import more 3D printers. Suggestive evidence also support the second and third prediction of the model.

JEL classification: F10, F23, O33.

Keywords: 3D printing, FDI, trade, technological change, transport costs.

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> “Companies are re-imagining supply chains: a world of networked printers where logistics may be more about delivering digital design files – from one continent to printer farms in another – than about containers, ships and cargo planes”
>
> — PWC report (2014), *3D printing and the new shape of industrial manufacturing*

1 Introduction

Three dimensional (3D) printing, also known as additive manufacturing, is emerging as a world-shattering technology. It allows the creation of objects by printing successive layers of different materials, mostly plastic or metal, instead of subtracting or cutting material from a large piece or a block (which is called “subtractive”manufacturing). With this new technology at hand, ordinary citizens could present their ideas to designers and easily turn them into real products using a relatively cheap 3D printing machine. Large 3D printers, which are capable of making objects up to a meter in diameter and three meters in height have also been developed for industrial use (e.g. delta-style 3D printers by SeeMeCNC). The main challenge faced by the developers is to improve the technology to create printers able to produce large objects at high speeds that can be used for mass production. Among the current industry leaders are Stratasys, EOS, and 3D Systems, with the last firm currently selling a kit for around 1,000 US$ for consumer use.

3D printing technology, invented by Chuck Hull, was patented in 1986. This technology was initially called *stereolithography*, which basically consisted of solidifying very thin layers of a special polymer using a laser. Hull founded one of the main market players in the business, 3D Systems, but he was unable to restrict competition and other technologies have been constantly developed since then (Zhang, 2014). Figure 1 shows the evolution of patents related to 3D printing technology in the US. We see that the number of patents has skyrocketed over the past years. This is confirmed by the Wohlers Report 2014 (2014), in which not only the patents granted but also the applications of patents in the US, which show a similar trend, are reported.

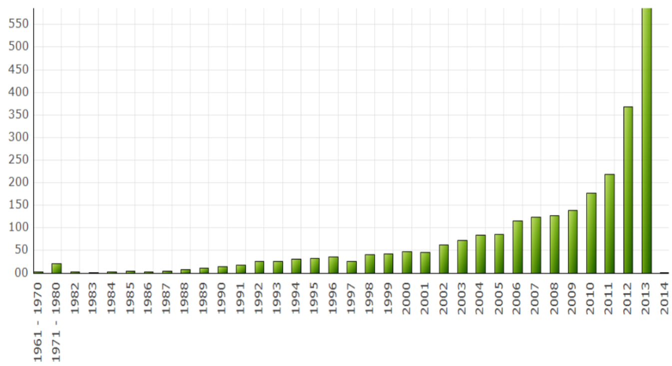

Figure 1: 3D Printing Patents

Source: Patent iNSIGHT Pro (2014)

3D printing can be considered as a disruptive technology because it completely changes the production process in several ways: i) production lines (assembly) can be reduced or could even disappear for many small manufactured products; ii) a regionalization process is likely to emerge because production can be located close to the main markets without any need of transporting goods over long distances; iii) product variety could radically increase because it will be easy to customize products and adapt them to consumer tastes; iv) there will be no need to keep inventories because design files can be sent instantaneously to any location in the world; v) the technology has a less damaging effect on the environment because it implies a cleaner production process with lower material waste and it shortens the routes for delivering goods, which in turn contributes to reductions in emissions originating in the transport sector; vi) it allows for the possibility to produce more with fewer workers, which raises labor productivity drastically. This latter effect might cause disruptions in labor markets in the short run, but could have beneficial effects in the long run, in particular, in aging societies like Western Europe and Japan, in which the labor force is already starting to shrink.

Examples for the successful use of 3D printing technologies abound – two of them are described in an article in *USA Today*[1]. The first one refers to Audiovox as an assembler of digital TVs for BMW headrests. Audiovox decided to use the technology to print a control button of the TVs, which saved the company incurring the tooling expenses and enabled it to deliver the pieces much faster. The second example is the production of infrared cameras for housing. Given that the supplier had to go through several design changes, the 3D printer served as an excellent production technology to cope efficiently with these kind of requests. Furthermore, The Guardian (2015)[2] illustrates how – even in construction – this technology could change production processes drastically. They describe the building of a villa within 1 month using only 8 workers, while without 3D printing it would have cost twice as much, taken 3 times as long, and have required 30 workers.

Of course, there are also drawbacks. Printing times are still substantial and particularly restrictive if thousands of pieces are requested within a short time frame. Moreover, some of the materials used are still not resistant enough (a property that carries over to the final product) and still have to go through severe testing in order to meet the standards required by governmental regulators. Finally, the costs of the printers – though they have been decreasing over time – are still high enough to be prohibitive for small companies, especially the bigger and more expensive printers that are able to make products out of metal powder. While the most affordable 3D printers are accessible to almost anyone at a cost of 1,000-2,000 US$, bigger printers, such as the ones required by Airbus and General Electric, can cost 1,000 times that price, according to the listed prices of 3D printers in Wohlers Report 2014 (2014). Another issue worth mentioning is that different environmental conditions in

[1] `http://usatoday30.usatoday.com/money/industries/manufacturing/story/2012-07-10/digital-manufacturing/56135298/1`, accessed 14th January 2015.

[2] `http://www.theguardian.com/cities/2015/feb/26/3d-printed-cities-future-housing-architecture`

different countries could change the characteristics of the powders used in the production process, altering the final product and prohibiting replicability (Stahl, 2013; Ford, 2014).

In sum, however, the cost-effectiveness of AM manufacturing seems to be unbeatable in comparison to existing technologies – particularly for pieces required in a small scale and with high degrees of complexity – and could challenge the competitive advantages of China and other low-wage countries as factories of the world. It might also reduce barriers to entry for potential manufacturers in many industries and could have important implications for national security and geopolitics.

The main aim of this paper is twofold. First, a theoretical model that investigates the impact of 3D printing on foreign direct investment (FDI) and international trade, besides the global transmission of this path-breaking invention is presented. The theoretical model predicts a product life-cycle-type development of production and trade: in the first stage, 3D printers are introduced in areas with high economic activity subject to high transport costs; in the second stage, technological progress in 3D printing machines leads to a gradual replacement of traditional production structures used in FDI with those relying on 3D printing techniques – at that stage, however, international trade remains unaffected; in the third stage, 3D printing machines are widely used and further technological progress in 3D printing leads to a gradual replacement of international trade by local production. The first prediction of the model is tested using a gravity model and the second and third predictions are evaluated by means of case studies, all to be found in the empirical section of the paper. The empirical results confirm the first prediction, while the case studies give some confirmation of the second and third predictions. To our knowledge this is the first paper that specifically analyzes 3D printing in the context of the new-new trade theory and that explores the (potential) global economic consequences of introducing this technology into the production process.

The paper is structured as follows. Section 2 describes the 3D printing industry and the available data series in more detail. Section 3 presents the theoretical framework, Section 4 is dedicated to our empirical analysis, and Section 5 concludes.

2 3D Printers' Production and distribution in the world market

Despite the fact that the industry has been existing for over two decades, it has only recently gained importance when the initial patents started to expire. Therefore, data on production, use, and trade of 3D printers is scarce. In terms of production of the printers, data is not easily accessible for the public since not all the companies that produce the printers are traded on the stock market and therefore the data are mostly confidential. As a result, we have to rely on information from newspaper articles and reports from consulting firms or independent organizations. As we can see in Figure 2, the number of industrial 3D printers sold has been increasing over time, especially since the mid 90's for the US.

Also for Germany, closely followed by Israel, a steady increase can be observed. It is worth mentioning the jump in the Israelian figure for the year 2013 and the corresponding decrease in the US for the same year. It can be explained by the merger of two companies, Stratasys Ltd. from the US and Stratasys Inc. and Object Ltd. from Israel and the fact that the resulting company was registered in Israel (Wohlers Report 2014, 2014).

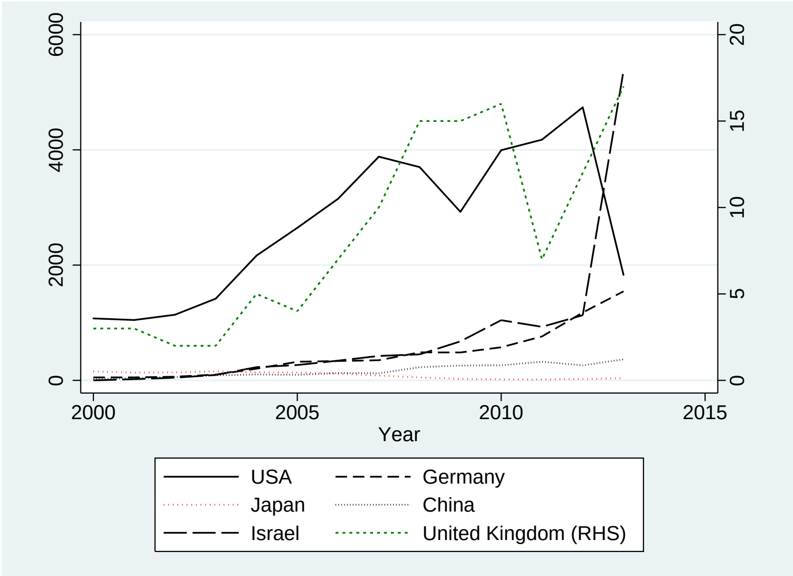

Figure 2: Printers sold in a selected group of countries

Source: Authors' calculations based on data from Wohlers Report (2014)

The main producers of industrial 3D printers are located in countries that are pioneers in 3D printing technology and where most patents are registered. This can be seen in Figure 3, which displays the amount of patents per country. The US is the leader, followed by China, Japan, and Germany. Most of the governments of these countries are financing research centers and initiatives to provide an impulse to the sector, since they firmly believe in its potential to benefit the economy in a variety of sectors – going from medicine to the aerospace industry. For example, in the United States the National Additive Manufacturing Innovation Institute was created in 2012 and President Obama referred to it in his Presidential speech in 2013: "A once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3-D printing that has the potential to revolutionize the way we make almost everything"[3]. During the same speech he announced three extra manufacturing hubs planned for the future "to turn regions left behind by globalization into global centers of high-tech jobs", and further: "I ask this Congress to [...] guarantee that the next revolution in manufacturing is made in America"[4]. Indeed, in January 2015 a new manufacturing innovation hub in Knoxville, Tennessee was announced[5][6]. In the

[3] http://edition.cnn.com/2013/02/13/tech/innovation/obama-3d-printing/
[4] http://edition.cnn.com/2013/02/13/tech/innovation/obama-3d-printing/
[5] https://www.whitehouse.gov/the-press-office/2015/01/09/fact-sheet-president-obama-announces-new-manufact
[6] Refer to Wohlers Report 2014 (2014) for more information on other initiatives.

case of China, 2013 was a crucial year for R&D investments in 3D printing since provincial, central, and city governments helped the sector by investing in the means of capital equipment and R&D support, and offered tax refunds, loans at low interest rates, and land to be used for construction. Moreover, in 2013 new 3D printing industrial parks and centers were developed in three provinces (see Wohlers Report 2014, 2014). The European Union also finances the development of the technology through several channels such as the European Space Agency or the European Union's Framework Funding.

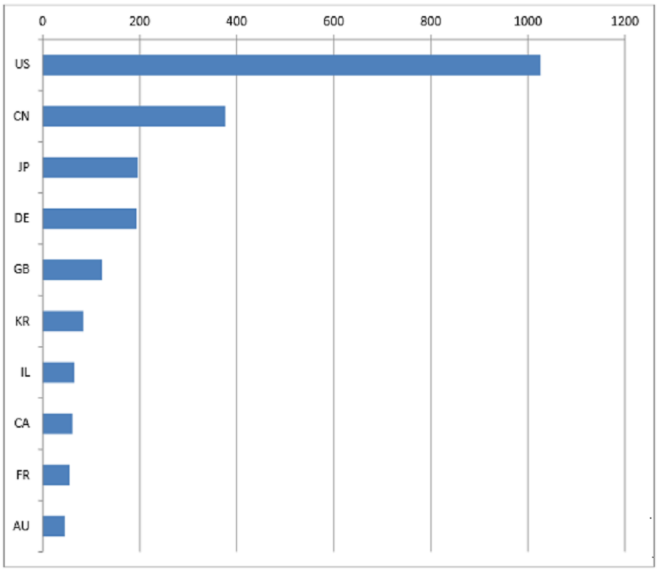

Figure 3: Amount of Patents related to Additive Manufacturing (selected countries)

Source: Intellectual Property Office (2013)

An important aspect of the 3D printing business is that the industry includes a number of closely related activities, namely the production of services, inputs, and materials used to print products, software development, printers, parts for final products, and the production of prototypes. Figure 4 displays the increase in parts for final products as a share of the whole 3D printing market (basically including services and total product revenues from 3D printing) (Wohlers Report 2014, 2014). We clearly observe that the share of parts has been steadily increasing over time, which indicates that more companies have started to include 3D printed parts in their final goods.

Another challenging issue is the analysis of international trade in 3D printers and related products, in order to measure adoption. We discuss the related problems in Section A.1 of the Appendix. As the best way to solve these issues we decided to consider the printers under the category 8477.80 of the Harmonized System. Figures 5 and 6 show the evolution over time of the volume and value of exports recorded for the main exporting countries. Both figures show that Germany is the main exporter, followed by China, the US (who had the most stable exports), Japan, the Republic of Korea, and finally Israel. Surprisingly, the US is only the third exporter in the ranking, which could be due to the

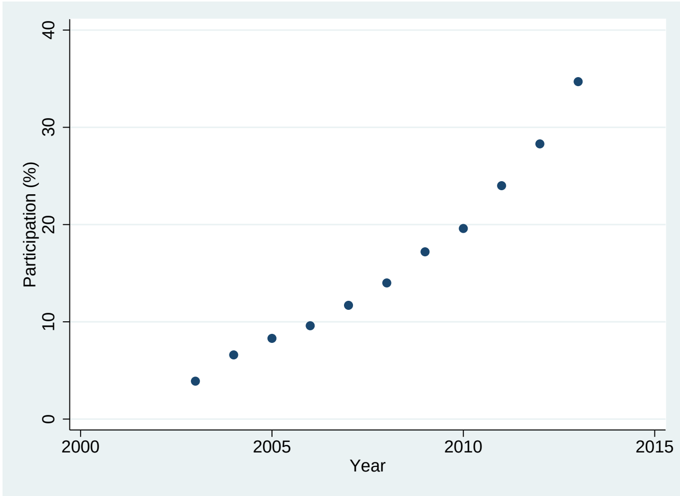

Figure 4: Participation of parts production for final goods in total revenues

Source: Authors' elaboration based on Wohlers Report 2014 (2014)

fact that trade is reported under different classifications, or simply because the printers produced in the US are mainly sold in the domestic market. It should be noted that there was an important decrease in the volume exported by China in 2007, which was not matched with a decrease in the value exported.

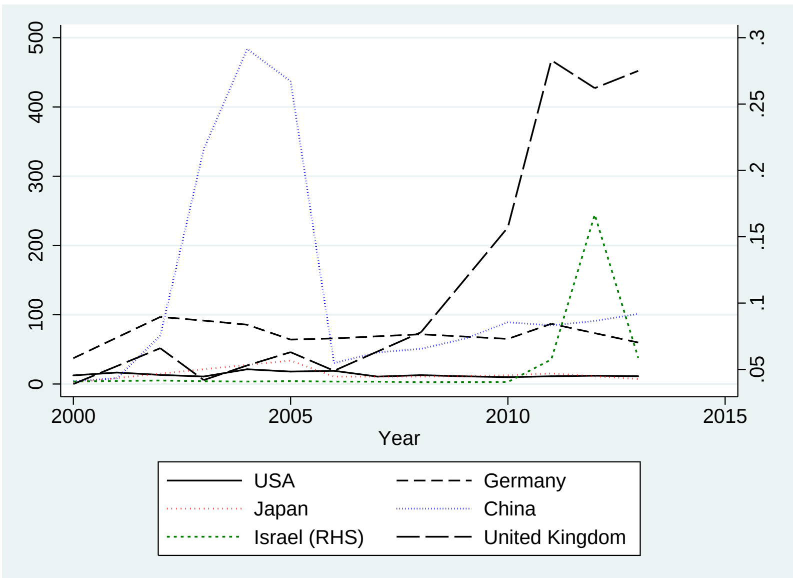

Figure 5: Volume of printers exported under the code 8477.80 (in thousands)

Source: Authors' calculations based on data from UN-Comtrade

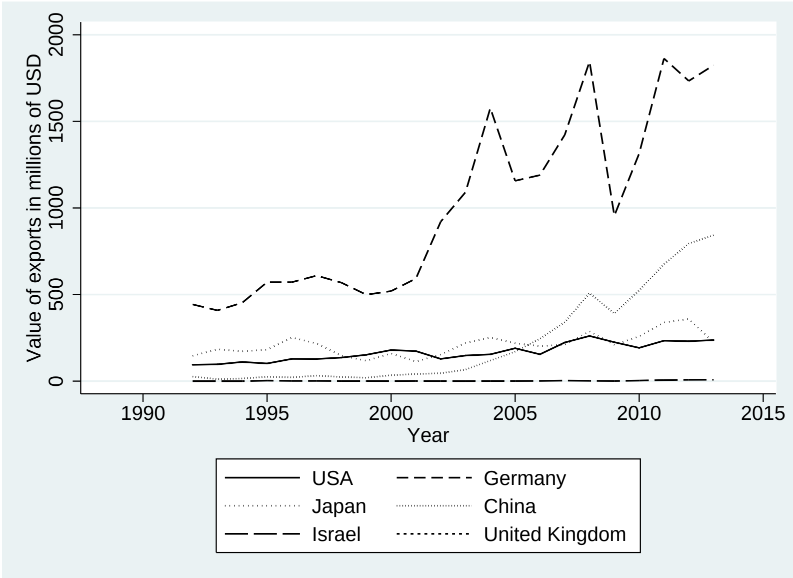

Figure 6: Value of printers exported under code 8477.80 (in millions of USD)

Source: Authors' calculations based on data from UN-Comtrade

3 The impact of the 3D printer on international trade: theory

Consider a world comprised of $i \in [1, n+1]$ open economies. In each economy there is a sector in which firms produce a homogenous good with a unitary labor input coefficient and another sector in which firms produce a continuum of manufactured goods $j \in (0,1)$. Following Melitz et al. (2004), homogenous goods can be costlessly traded, while manufactured goods can be sold in the home country (no transport costs), they can be exported to other countries (subject to iceberg transport costs $\tau > 1$), or they can be produced directly in the destination country by subsidiaries established via greenfield FDI (no transport costs). Production for the home market is subject to the fixed costs cf_D, while production for the export market is subject to the fixed costs $cf_X > cf_D \cdot \tau^{1-\epsilon}$. In contrast to Melitz et al. (2004), FDI can occur in two different forms: a) firms incur a fixed investment of cost $cf_I > cf_X \cdot \tau^{\epsilon-1}$ to establish a foreign subsidiary that replicates the parent's domestic production technology, b) firms incur a fixed investment of cost $cf_{3D} > cf_I$ to establish a foreign subsidiary based on the technology of 3D printing machines. The use of 3D printers implies that the subsidiary utilizes a superior production technology as compared to the parent in the home country. We conceptualize this by assuming that the factor input requirement for the production of each good in the subsidiary is reduced by the amount ξ in relation to the parent company. This is a minimum-invasive way of modeling the advantage of 3D printing over traditional production technologies and captures, as a short-cut formulation, the channels i), iv), v), and vi) as outlined in the introduction. Furthermore, since the implementation of 3D printing is associated with FDI and therefore regionalized, the formulation also takes into account channel ii). In line with the literature on trade with firm-specific heterogeneity[7], we assume that the only variable production factor is labor, which earns the wage rate w, and that, upon entering the industry, a firm draws its productivity level $\theta(j)$ from the distribution $G(\theta)$. This implies that the variable production cost is given by $w/\theta(j)$.

At the consumption side, we assume that households are identical across economies and have utility functions with a constant elasticity of substitution $\epsilon = 1/(1-\alpha) > 1$ between the different varieties. Following the notation of Helpman (2006), the demand for each variety is given by $x(j) = Ap(j)^{-\epsilon}$ with $x(j)$ being the quantity of good j, $p(j)$ being its price, and A denoting the demand level as determined by household's income. The standard profit maximization problem in this setting leads to the familiar outcome that the profit-maximizing pricing strategy for firms is to charge a mark-up over marginal cost (cf. Dixit and Stiglitz, 1977; Melitz, 2003). This implies that firms charge the price $p(j)_D = w/[\alpha\theta(j)]$ on the domestic market, the price $p(j)_X = w\tau/[\alpha\theta(j)]$ in the destination country if firms choose to export, the price $p(j)_I = w/[\alpha\theta(j)]$ in the destination country if firms choose to open a foreign subsidiary that is based on the domestic (traditional) production technology, and the price $p(j)_{3D} = w/[(1+\xi)\alpha\theta(j)]$ in the destination country if firms choose to open a foreign subsidiary that is based upon the superior 3D printing technology.

For the sake of expositional clarity, we suppress the index j from now on. In our setting, a partitioning of firms occurs as follows: very unproductive firms that do not expect to recover the fixed costs of production, choose to exit immediately. Firms that are productive enough to supply to the home market but not to the foreign market earn profits

$$\begin{aligned}\pi_D &= \theta^{\epsilon-1}(1-\alpha)A\left(\frac{w}{\alpha}\right)^{1-\epsilon} - cf_D \\ &\equiv \Theta B - cf_D, \end{aligned} \tag{1}$$

where we follow the notation of Helpman (2006) such that $\Theta = \theta^{\epsilon-1}$ and $B = (1-\alpha)A\,(w/\alpha)^{1-\epsilon}$.

Let the threshold level of productivity below which the firm would choose to shut down be given by Θ_D. In this case there exists a productivity level $\Theta_X > \Theta_D$ above which firms can recover the additional fixed costs of exporting to the destination country i. These firms earn profits as given by

$$\begin{aligned}\pi_D + \pi_X &= \theta^{\epsilon-1}(1-\alpha)A\left(\frac{w}{\alpha}\right)^{1-\epsilon} - cf_D + \tau^{1-\epsilon}\theta^{\epsilon-1}(1-\alpha)A^i\left(\frac{w}{\alpha}\right)^{1-\epsilon} - cf_X \\ &\equiv \Theta B - cf_D + \tau^{1-\epsilon}\Theta B^i - cf_X, \end{aligned} \tag{2}$$

where $B^i = (1-\alpha)A^i\,(w/\alpha)^{1-\epsilon}$ refers to the demand level (and hence economic activity)

[7] See for example Eaton and Kortum (2002), Melitz (2003), Bernard et al. (2003), Melitz et al. (2004), and Helpman (2006) for different approaches.

in the destination country i.

Greenfield FDI has the advantage that goods can be sold in the destination country without the need to incur transport costs. The disadvantage of FDI is mainly the higher fixed cost as compared to exporting because a new plant has to be established abroad. Consequently, more productive firms with a productivity level above $\Theta_I > \Theta_X$ find it profitable to exit the export business to country i and instead to open a subsidiary there. These firms earn profits

$$\begin{aligned}\pi_D + \pi_I &= \theta^{\epsilon-1}(1-\alpha)A\left(\frac{w}{\alpha}\right)^{1-\epsilon} - cf_D + \theta^{\epsilon-1}(1-\alpha)A^i\left(\frac{w}{\alpha}\right)^{1-\epsilon} - cf_I \\ &\equiv \Theta B - cf_D + \Theta B^i - cf_I \end{aligned} \tag{3}$$

but they still do not invest in the new technology of 3D printing machines when establishing their subsidiaries. The reason is that 3D printing facilities, while leading to lower variable production costs, come with a higher fixed cost than traditional FDI.

Firms with productivity levels above Θ_{3D} will choose to base their subsidiary in the foreign economy on the superior 3D printing technology. Initially, Θ_{3D} will be very high because the 3D printing technology is new and the introduction of any new technology is associated with high fixed costs. Consequently, immediately after the invention of 3D printing $\Theta_{3D} > \Theta_I$ will hold for sure. Over time, however, technological progress with respect to 3D printing will lead to falling fixed costs, such that other situations become possible as we will see below. Firms pursuing FDI via advanced 3D printing technologies earn profits

$$\begin{aligned}\pi_D + \pi_{3D} &= \theta^{\epsilon-1}(1-\alpha)A\left(\frac{w}{\alpha}\right)^{1-\epsilon} - cf_D + \theta^{\epsilon-1}(1-\alpha)A^i\left[\frac{w}{(1+\xi)\alpha}\right]^{1-\epsilon} - cf_{3D} \\ &\equiv \Theta B - cf_D + \Theta(1+\xi)^{\epsilon-1}B^i - cf_{3D}. \end{aligned} \tag{4}$$

To be able to illustrate this situation graphically, we follow Helpman (2006) and restrict our attention to the case of equally-sized countries, which implies that $A^i = A$ for all i. The initial situation (introduction phase) is depicted in Figure 7 that shows the profit components due to domestic sales (π_D), due to exports (π_X), due to FDI relying on traditional production technologies (π_I), and due to FDI relying on advanced 3D printing technologies (π_{3D}) for the case of high fixed costs of 3D printing machines. The fixed costs are depicted on the negative part of the y-axis, while productivity $\Theta = \theta^{\epsilon-1}$ is depicted on the x-axis. Similar to Melitz et al. (2004) and Helpman (2006), firms with a productivity level below Θ_D shut down, firms with productivity $\Theta_D < \Theta < \Theta_X$ produce for the home market only, firms with productivity $\Theta_X < \Theta < \Theta_I$ produce for the home market and export, and firms with productivity $\Theta_I < \Theta < \Theta_{3D}$ pursue FDI relying on the traditional production techniques. Note that the slopes of the lines π_D and π_I are the same because the associated type of FDI just replicates the home market technology in the foreign economy, while the slope of the line π_X is lower because iceberg transport

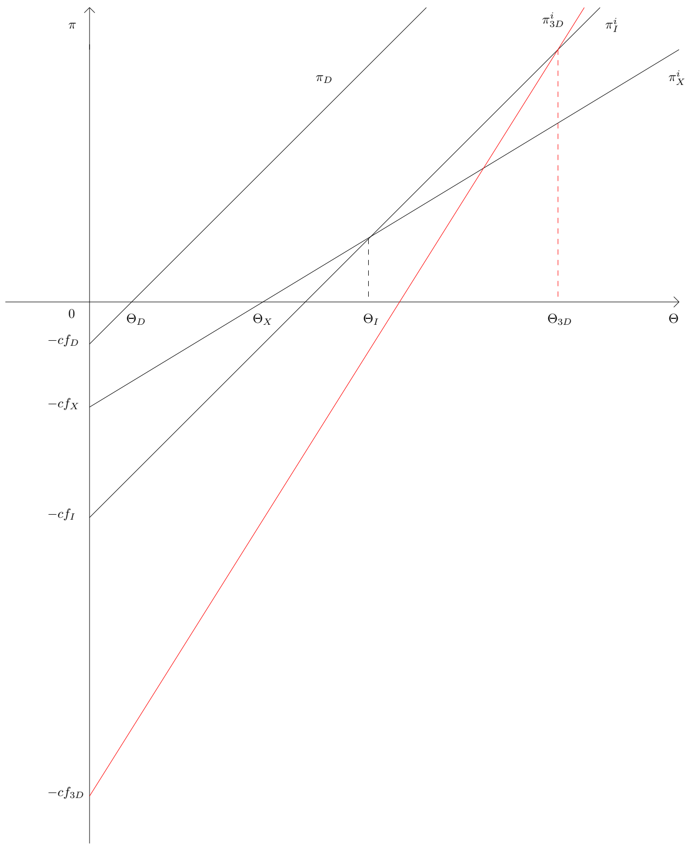

Figure 7: The effect of 3D printing technology on FDI and trade (introduction phase)

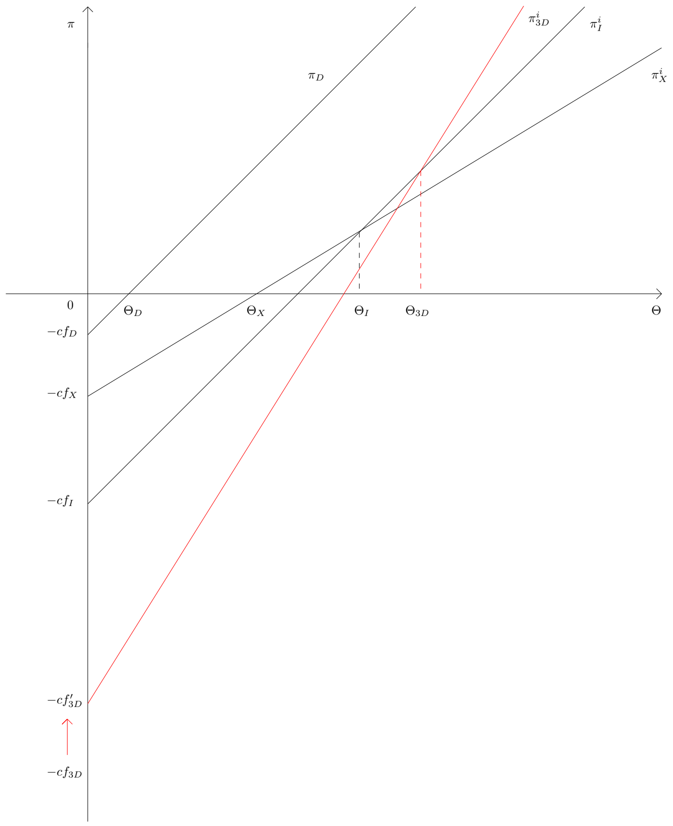

Figure 8: The effect of 3D printing technology on FDI and trade (growth phase)

costs reduce profits per unit shipped. The new element is the red line that refers to the additional profits due to FDI via 3D printing technologies. This line is steeper than all the other lines because the use of 3D printers reduces the variable costs by the amount ξ. At the stage depicted in Figure 7, the fixed costs of 3D printing technologies are still very high, such that the productivity level necessary for a firm to invest in this technology is large ($> \Theta_{3D}$). In this situation, only the most productive firms choose to establish subsidiaries based upon 3D printing technologies.

Now suppose that technological progress reduces the fixed cost of 3D printing technologies. This situation (growth phase) is depicted in Figure 8, where cf_{3D} is reduced such that the red line of additional profits due to FDI via 3D printing technologies shifts upward. This implies that FDI relying on traditional technologies decreases and is gradually replaced by FDI relying on 3D printing technologies. In this situation, international trade still remains unaffected by technological progress with respect to 3D printing machines. The reason is that the variable cost savings of 3D printing technologies are large enough to compete with traditional FDI, whose fixed cost is larger than the fixed cost of exporting. At the same time, the variable cost savings of 3D printing technologies are still not large enough to compete with the firms that only face the lower fixed cost of exporting.

Finally, suppose that technological progress reduces the fixed cost of 3D printing tech-

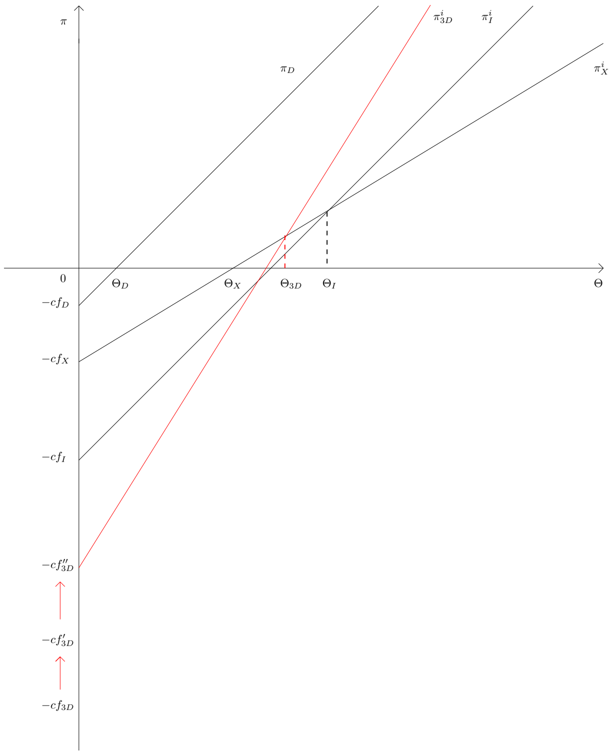

Figure 9: The effect of 3D printing technology on FDI and trade (maturity phase)

nologies further, as shown in Figure 9. At this stage (maturity phase) the variable cost savings of 3D printing technologies are large enough to make these firms start competing with the exporters. This implies that $\Theta_I > \Theta_{3D}$ and all FDI is based upon advanced 3D printing technologies. Additional reductions in fixed costs could even lead to a partial replacement of trade in manufactured goods by FDI. Note that trade in homogenous goods (e.g. in the materials used by the 3D printers) could still increase.

An analogous result would be obtained if technological progress came in the form of higher efficiency (bigger ξ). In this case technological progress in 3D printing would lead to a counterclockwise rotation of π^i_{3D} as displayed by the red lines in Figures 7 to 9. Consequently, technological progress in 3D printing would first imply that traditional FDI is replaced by FDI based upon 3D printing technologies and only later would trade in manufactured goods be replaced. The qualitative result is the same as in the case in which technological progress with respect to 3D printers assumes the form of reductions in the fixed costs of printers.

Our framework implies the following testable predictions: i) the introduction of 3D printers predominantly takes place in areas with high economic activity (countries or regions with a large A^i) that are contemporaneously subject to high transport costs; ii) initially, technological progress with respect to 3D printing machines leads to a gradual replacement of FDI using traditional production structures with FDI that uses 3D printing techniques – at that stage international trade stays unaffected; iii) in later stages, when

3D printing machines are already widely used, further technological progress with respect to 3D printers leads to a gradual replacement of international trade. Given that the 3D printing technology is still quite young, lack of appropriate time series data prevent us from testing some of these implications. In Section 4 below we present a test of prediction i) and a case study is outlined that supports predictions ii) and iii). With the progress of time and with more publicly available information on the adoption of 3D printing by private companies, we hope to extend the empirical assessment of the theoretical predictions in future research.

4 Empirical Evidence

4.1 Determinants of bilateral trade

In this section we use a gravity model of trade, which is nowadays considered the workhorse in the estimation of the determinants of bilateral trade (Feenstra, 2002; Head and Mayer, 2014). This model has been widely used in the recent literature to estimate the effects of different components of trade costs on trade, as well as to estimate the effects of a number of policy variables. Since we are mainly interested in the effects of demand in the destination country and the effects of transport costs on the adoption of 3D printers, we consider it appropriate for our purposes. In particular, it is useful to test the first prediction derived from the theoretical model (Section 3), which states that countries subject to higher transport costs and with a high domestic demand level will be among the earliest adopters of the technology.

Based on Anderson and van Wincoop (2003), we consider a number of country-specific and bilateral factors as determinants of bilateral trade. Since we lack comparable data on trade and domestic sales to properly assess the actual adoption per country, we only use trade statistics and are unable to consider printers that are produced locally and that are sold in the domestic market. Caselli and Coleman (2001) also use trade data to proxy for adoption of computers. Trade is measured using the code 8477.80 from UN-Comtrade as a proxy for trade in 3D printers as captured by X_{ij}. We considered the quantity traded because there is a wide dispersion in the values of printers (see Wohlers Report 2014 (2014) for a selected list of the available printers and the corresponding prices) and in these cases the quantity is a better unit of measurement (Vido and Prentice, 2003). Moreover, if there is an innovation such that printers are reduced in price, fewer "value" is traded but that is not representative of higher adoption. Data on GDPs were obtained from the World Development Indicators and from the World Bank. Distance (*dist*) refers to the geographical distance between capital cities of the trading countries, *rta* denotes regional trade agreements as a binary variable[8], common language (*comlang*) is a dummy variable that takes the value of 1 if both countries share an official language and the value

[8] This variable is constructed with information from Jose De Sousa's website (`http://jdesousa.univ.free.fr/data.htm`)

of zero otherwise; *colony* is a dummy variable that takes the value of 1 if two countries ever shared a colonial relationship and the value of zero otherwise. All these dummy variables were obtained from CEPII. The multilateral resistance terms P_i and P_j are controlled for by adding continental dummies, country dummies, or alternatively using the Bonus Vetus OLS approximation (Baier and Bergstrand, 2009).

The equation we estimate has the following form (for the panel analysis a further sub-index t and a set of year dummies are added):

$$\ln X_{ij} = \beta_0 + \beta_1 \ln GDP_i + \beta_2 \ln GDP_j + \beta_3 \ln trancost_{ij} + \beta_4 \ln dist_{ij} + \beta_5 rta_{ij} + \\ + \beta_6 comlang_{ij} + \beta_7 colony_{ij} + \beta_8 \ln P_i + \beta_9 \ln P_j + u_{ij}, \tag{5}$$

where β_k for $k = 0, \ldots 7$ denote the parameters to be estimated.

Several proxies for transport costs of 3D printers are considered. The first is the ad-valorem equivalent of transporting goods between countries obtained from the OECD website[9] and is specific for goods classified under Chapters 84, 87, and 90 of the HS. These three categories were chosen since they include parts of automobiles and airplanes (Chapters 84 and 87) and medical prosthetics and hearing aids (Chapter 90), as examples of products already being produced with 3D printing. Since the data are only available until 2007, we used the 2007 value also for more recent years. Based on the available information, the dataset for the cross-section[10] includes 106 exporting countries (when including the zeroes in the dependent variable, otherwise 52) and 33 importing countries (OECD countries only). The OECD transport cost dataset reports unitary and ad-valorem transport costs. We considered the ad-valorem measure since it better reflects the impact of transportation costs – Hummels (2007) shows that transport costs relative to the price of the good have not fallen across time for bulk cargo, and they have remained fairly stable for liner shipping, unlike the value per ton (Venables and Behar, 2010). This transport cost variable is only available for exports to OECD countries. Using this proxy for transport costs, we are able to estimate the gravity model using panel data for the period from 1997 to 2013. In addition, we also estimate the model for a single cross-section using the trade quantity and controls for the year 2013. This latter estimation is done so as to be able to compare these results with those obtained by using another proxy for transport costs that was collected for a single cross-section and is described in what follows.

We also gathered transport cost data for two packages from online inquiries in the Fedex website. Summary statistics for the same can be found in Table A3 and in Table A4 of the Appendix. For the first item, the price and dimensions correspond to a package described as hearing aids that is priced at 3,000 US$ and weighs a kilogram, sent with a Fedex Small Box with Fedex International Economy[11]. For the second one, we considered a box of machinery (could also be applied to parts of) with a volume of

[9] `https://stats.oecd.org/Index.aspx?DataSetCode=MTC`

[10] The sample varies slightly in the panel specification.

[11] We consulted the internet for prices of customized hearing aids that are produced with the use of 3D printing and this was an average price for an equipment of medium quality.

0.6mtsx0.6mtsx0.6mts. It was valued at 2,500 US$, with a weight of 25 kilograms and service was Fedex International Economy Freight. For both items we obtained information for sending the package from the US and China to about 120 destinations (capital cities) [12]. We considered that the shipment would take place one week later than when the data was collected and we considered the UPS Air Freight Direct[13].

Using the data described above, we estimate a number of gravity models using OLS and the Pseudo Poisson Maximum Likelihood estimator (PPML). The second estimator is especially useful because it allows to include the zeroes in exports and allows for the presence of heteroscedasticity. In Tables 1, 2, and 3 we report the estimation results for Equation (5) obtained with OLS and PPML for the three different product groups. In columns (1) and (4) we control for continent of origin and destination of the countries, whereas in column (2) country dummies are included (origin and destination) and in columns (3) and (5) we control for multilateral resistance using the Bonus Vetus specification.

The results show that estimated coefficients for the GDP variables, which proxy for the level of economic activity, are important determinants of trade in 3D printing machines. The estimated income elasticities are in most cases higher for the exporter country than for the importer, with only one exception (model 5). The magnitudes vary between 0.77 and 1.48 and 0.53 and 1.12, respectively. The latter indicates that an increase in income in the destination market of 5 percent leads to an increase in exports of 3D printers of around 3-5 percent. The transport costs variable has a positive and statistically significant association with exports of 3D printers (at the 1-10 percent level) and this result is mostly robust across different specifications. The elasticity of trade with respect to transport costs is relatively high in magnitude indicating that a 1 percent increase in the ad-valorem transport cost is associated with an increase in exports of 3D printers of around 0.7 percent (model 2, Table 1). Model 2, which includes country of origin and destination dummies, is probably the most appropriate to obtain an unbiased coefficient estimate of the transport costs variable because it controls for all the heterogeneity that is country-specific. The main drawback is that the coefficients of GDPs cannot be estimated. Regarding the rest of the control variables, in general they have the expected signs and magnitudes, although the regional trade agreement dummy is not statistically significant in most of the specifications. This is probably due to the very low level of tariffs or even their absence for this product line for the countries in the sample. The parameter estimates of the GDPs have the expected values (close to unity) and the estimated coefficient for distance is negative and statistically significant in most specifications. Cultural variables, namely common language and common colony also exhibit the expected positive sign and are statistically significant in most cases.

Summarizing, the empirical results using the OECD measures of transport costs for the different product groups are in line with the first prediction of the theoretical model

[12] For the US, New York was considered since it exceeds the population and economic activity of Washington D.C..

[13] The data of Fedex throughout the months of July and February 2015 from `https://www.fedex.com/ratefinder/home?link=4&cc=US&language=en`.

indicating that the introduction of 3D printers predominantly takes place in areas with high economic activity [positive and statistically significant effect of GDP of destination (j)] that are contemporaneously subject to high transport costs of goods that are being produced with 3D printing [positive and statistically significant effect of lntcoecd]. Since the transport cost variable is used with lags in the gravity model, the value being for the year 2007, we can rule out endogeneity issues concerning, for example, reverse causality.

Table 1: Cross-sectional regressions with OECD measure of transport cost (Chapter 84)

	OLS		OLS - BV	PPML	PPML - BV
	(1)	(2)	(3)	(4)	(5)
lntcoecd	0.605	0.738	1.401	0.521	1.066
	(0.248)**	(0.333)**	(0.250)***	(0.272)*	(0.359)***
lndist	-1.034	-1.591	-1.033	-1.399	-1.010
	(0.218)***	(0.224)***	(0.357)***	(0.151)***	(0.629)
comlang	0.594	1.053	0.720	0.128	0.809
	(0.279)**	(0.339)***	(0.314)**	(0.188)	(0.290)***
colony	-0.126	0.491	0.770	0.481	1.162
	(0.414)	(0.421)	(0.200)**	(0.197)**	(0.537)**
rta	0.296	-0.357	0.286	0.684	0.610
	(0.201)	(0.386)	(0.271)	(0.164)***	(0.587)
lngdpi	1.120		0.795	1.477	0.815
	(0.098)***		(0.102)***	(0.111)***	(0.071)***
lngdpj	0.721		0.627	1.072	1.046
	(0.093)***		(0.095)***	(0.132)***	(0.103)***
(Pseudo)R^2	0.43	0.72	0.38	0.70	0.47
N	359	359	359	856	856
Dummy Var.	Continent	Countries	-	Continent	-

Notes: Standard errors are clustered at the importer level. One asterisk indicates significance at the 10% level, two asterisks indicate significance at the 5% level, and three asterisks indicate significance at the 1% level. A constant term is included in all regressions but the coefficient is not reported. In columns (1) to (3) the log of the amount of printers is the dependent variable, while in (4) and (5) it is the quantity itself. Columns (3) and (5) control for multilateral resistance with the Baier and Bergstrand (2009) methodology – each bilateral trade cost is included using the following formula: $\ln t_{ijt} + \frac{1}{N}\sum_{j=1}^{N}\ln t_{ijt} - \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\ln t_{ij} + \frac{1}{N}\sum_{i=1}^{N}\ln t_{ijt}$.

Table 4 shows the cross-sectional results using alternative transport costs measures, for two different packages. In most cases – either with the OLS or with the Poisson Pseudo-Maximum likelihood estimator – we obtain positive and statistically significant estimates for the GDP coefficient of the importer country. For the transport costs, we only obtain positive and statistically significant coefficients for the Poisson estimator. A reason for this could be that this is a very reduced sample and therefore adding more information is important. Overall, the results are mostly consistent with the results of the previous

Table 2: Cross-sectional regressions with OECD measure of transport cost (Chapter 87)

	OLS		OLS - BV	PPML	PPML - BV
	(1)	(2)	(3)	(4)	(5)
lntcoecd	0.617***	0.510*	0.936***	0.379**	0.389*
	(0.164)	(0.273)	(0.232)	(0.167)	(0.203)
lndist	-1.303***	-1.741***	-1.451***	-1.335***	-0.533
	(0.207)	(0.246)	(0.441)	(0.163)	(0.491)
comlang	0.298	0.855**	0.242	0.069	0.705**
	(0.235)	(0.335)	(0.499)	(0.172)	(0.322)
colony	0.001	0.611	1.107*	0.605***	1.544***
	(0.398)	(0.461)	(0.587)	(0.149)	(0.527)
rta	0.382*	-0.324	-0.213	0.710***	0.614
	(0.209)	(0.407)	(0.357)	(0.168)	(0.405)
lngdpi	1.173***		0.785***	1.458***	0.775***
	(0.101)		(0.101)	(0.105)	(0.077)
lngdpj	0.745***		0.582***	1.118***	1.045***
	(0.099)		(0.112)	(0.139)	(0.094)
N	339	339	339	755	755
(Pseudo)R^2	0.453	0.721	0.356	0.718	0.411
Dummy Var.	Continent	Countries	-	Continent	-

Notes: Standard errors are clustered at the importer level. One asterisk indicates significance at the 10% level, two asterisks indicate significance at the 5% level, and three asterisks indicate significance at the 1% level. A constant term is included in all regressions but the coefficient is not reported. In columns (1) to (3) the log of the amount of printers is the dependent variable, while in (4) and (5) it is the quantity itself. Columns (3) and (5) control for multilateral resistance with the Baier and Bergstrand (2009) methodology – each bilateral trade cost is included using the following formula: $\ln t_{ijt} + \frac{1}{N}\sum_{j=1}^{N} \ln t_{ijt} - \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} \ln t_{ij} + \frac{1}{N}\sum_{i=1}^{N} \ln t_{ijt}$.

Table 3: Cross-sectional regressions with OECD measure of transport cost (Chapter 90)

	OLS		OLS - BV	PPML	PPML - BV
	(1)	(2)	(3)	(4)	(5)
lntcoecd	0.512***	0.385**	0.938***	0.351**	0.333
	(0.182)	(0.170)	(0.222)	(0.175)	(0.251)
lndist	-1.110***	-1.573***	-1.236***	-1.228***	-0.402
	(0.212)	(0.245)	(0.387)	(0.175)	(0.509)
comlang	0.314	0.826***	0.406	0.154	0.683**
	(0.229)	(0.298)	(0.466)	(0.198)	(0.321)
colony	-0.071	0.593	0.910	0.534***	1.407**
	(0.418)	(0.469)	(0.612)	(0.190)	(0.568)
rta	0.331*	-0.442	-0.286	0.692***	0.581
	(0.183)	(0.334)	(0.312)	(0.170)	(0.399)
lngdpi	1.146***		0.809***	1.442***	0.766***
	(0.091)		(0.089)	(0.108)	(0.074)
lngdpj	0.774***		0.563***	1.097***	1.044***
	(0.096)		(0.101)	(0.128)	(0.099)
N	339	339	339	714	714
(Pseudo)R^2	0.453	0.721	0.356	0.718	0.411
Dummy Var.	Continent	Countries	-	Continent	-

Notes: Standard errors are clustered at the importer level. One asterisk indicates significance at the 10% level, two asterisks indicate significance at the 5% level, and three asterisks indicate significance at the 1% level. A constant term is included in all regressions but the coefficient is not reported. In columns (1) to (3) the log of the amount of printers is the dependent variable, while in (4) and (5) it is the quantity itself. Columns (3) and (5) control for multilateral resistance with the Baier and Bergstrand (2009) methodology – each bilateral trade cost is included using the following formula: $\ln t_{ijt} + \frac{1}{N}\sum_{j=1}^{N} \ln t_{ijt} - \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} \ln t_{ij} + \frac{1}{N}\sum_{i=1}^{N} \ln t_{ijt}$.

tables. Distance is not always significant, which could be due to the restricted sample and the use of continent fixed effects. To control for multilateral resistance and heterogeneity of the importer, we included continent dummies of the importer. Instead of the GDP of the importer we included a dummy for the US, which has a negative coefficient. This could indicate that this country exports less printers than what gravity would predict. Since the country is a pioneer in 3D printing, it could be the case that a substantial amount of printers remains in the local economy.

Table 4: Cross-sectional regressions with Fedex measure of transport cost

	Large package				Hearing aids package			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
lnfedex	0.137	1.213***	-0.140	0.793*	0.152	1.153**	0.008	1.147**
	(0.410)	(0.432)	(0.414)	(0.430)	(0.546)	(0.533)	(0.569)	(0.554)
lndist	-0.231	-0.579**	-0.412*	-0.330	-0.246	-0.430**	-0.454**	-0.238
	(0.196)	(0.226)	(0.212)	(0.221)	(0.190)	(0.192)	(0.217)	(0.200)
comlang	0.116	0.685**	-0.048	0.617**	0.120	0.523	0.000	0.576**
	(0.329)	(0.338)	(0.361)	(0.247)	(0.312)	(0.367)	(0.352)	(0.270)
colony	0.585	0.351	0.981**	0.771**	0.553	0.437	0.984**	0.859**
	(0.371)	(0.363)	(0.427)	(0.387)	(0.364)	(0.396)	(0.419)	(0.391)
rta	1.317***	2.033***	0.979***	1.712***	1.203***	1.902***	0.859***	1.715***
	(0.279)	(0.294)	(0.297)	(0.338)	(0.280)	(0.320)	(0.311)	(0.336)
lngdpj	0.843***	0.779***	0.810***	0.757***	0.837***	0.676***	0.824***	0.722***
	(0.064)	(0.062)	(0.065)	(0.055)	(0.057)	(0.047)	(0.058)	(0.057)
usa	-2.850***	-2.293***	-2.860***	-2.242***	-2.951***	-3.087***	-2.827***	-2.860***
	(0.255)	(0.312)	(0.243)	(0.273)	(0.256)	(0.461)	(0.271)	(0.377)
N	174	207	174	207	177	211	177	211
(Pseudo) R-squared	0.690	0.699	0.721	0.752	0.683	0.677	0.716	0.770
Dummy Var.	-	-	Cont. (d)	Cont. (d)	-	-	Cont. (d)	Cont. (d)
Origin	USA and China							

Notes: Robust standard errors for the OLS regressions. One asterisk indicates significance at the 10% level, two asterisks indicate significance at the 5% level, and three asterisks indicate significance at the 1% level. A constant term is included in all regressions but the coefficient is not reported. Columns (1),(3),(5) and (7) are estimated with OLS and the log of the amount of printers is the dependent variable, while in (2), (4), (6) and (8) it is the quantity itself the dependent variable and the estimator is PPML.

In Tables 5, 6, and 7 the panel results are presented. Also in this case, we consistently find positive coefficients for most of the transport cost measures, as predicted by the theoretical model. The estimated coefficients for the variable of interest are in nearly all models slightly lower in magnitude to the cross-sectional estimates. Moreover, the GDP of the destination country is also positive and statistically significant, which is again in line with the model predictions. The magnitude of the effects is also slightly lower than in the cross-sectional regressions, with the only exception of model (5) that includes zeroes in the dependent variable. Consequently, in the panel specification the inclusion of zeroes magnifies the effect of the variables of interest. This is in accordance with what could be expected, since including the data points for which there is no trade increases the transport cost and income elasticities, indicating that the bias of not considering the absence of trade is a downward bias. The results for the transport costs (as well as the bilateral variables distance, colony, rta, and common language) do not seem to be robust to the Poisson with the Bonus Vetus adjustment. A reason could be that the demeaning of the data is wiping out most of the variability. Counter-intuitive results with an opposite sign of the estimated coefficient for some traditional gravity variables have also been reported by Berden et al. (2014) and Portugal-Perez and Wilson (2012).

Table 5: Panel regressions with OECD transport cost measure (Chapter 84)

	OLS		OLS - BV	PPML	PPML - BV
	(1)	(2)	(3)	(4)	(5)
lntcoecd	0.348***	0.210*	0.430**	1.816***	0.231
	(0.130)	(0.119)	(0.169)	(0.406)	(0.310)
lndist	-0.893***	-1.085***	-0.813***	-1.259***	-0.991
	(0.143)	(0.117)	(0.229)	(0.243)	(0.744)
comlang	0.394**	0.878***	0.609**	0.644*	0.723*
	(0.188)	(0.169)	(0.238)	(0.337)	(0.398)
colony	-0.456*	0.215	0.366	-0.739***	-2.795
	(0.248)	(0.205)	(0.333)	(0.284)	(2.893)
rta	0.526**	0.410**	0.347	1.090**	-0.575
	(0.233)	(0.194)	(0.338)	(0.454)	(1.358)
lngdpi	0.987***	0.711***	0.687***	1.187***	0.746***
	(0.053)	(0.191)	(0.047)	(0.136)	(0.073)
lngdpj	0.551***	0.581***	0.440***	1.136***	0.773***
	(0.062)	(0.182)	(0.045)	(0.186)	(0.088)
N	3,894	3,894	3,894	12,531	12,531
(Pseudo)R^2	0.376	0.575	0.318	0.272	0.030
Dummy Var.	Continent	-	-	Continent	-

Notes: Standard errors clustered at the country-pair level. One asterisk indicates significance at the 10% level, two asterisks indicate significance at the 5% level, and three asterisks indicate significance at the 1% level. A constant term is included in all regressions but the coefficient is not reported. In columns (1) to (3) the log of the amount of printers is the dependent variable, while in (4) and (5) it is the quantity itself. Columns (3) and (5) control for multilateral resistance with the Baier and Bergstrand (2009) methodology – each bilateral trade cost is included using the following formula: $\ln t_{ijt} + \frac{1}{N}\sum_{j=1}^{N} \ln t_{ijt} - \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} \ln t_{ij} + \frac{1}{N}\sum_{i=1}^{N} \ln t_{ijt}$. All columns include time dummies. Due to convergence problems of the PPML estimator were encountered when trying to estimate the equivalent to (2) with PPML.

In a nutshell, using alternative transport cost measures and also exploiting the time series dimension of the data we find that countries subject to higher transport costs import more goods classified under code 8477.80, which is the code that includes 3D printers. In addition, the GDP of the destination country is positive and statistically significant, also in line with gravity theory and with our model predictions.

4.2 Industrial applications of 3D printing: medicine and the hearing aid industry

The use of 3D printers around the world is illustrated in Figure 10. The map gives a preview of how the printers of the 3DHubs are distributed across 150 countries. 3DHubs is a network of 3D printers that aims to help people who want to print its customized product find an outlet or a "hub" close to their location. Though these are most likely consumer use 3D printers with a limited purpose in manufacturing, it stills provides an idea of how the technology is being adopted throughout the world.

Table 6: Panel regressions with OECD transport cost measure (Chapter 87)

	OLS		OLS - BV	PPML	PPML - BV
	(1)	(2)	(3)	(4)	(5)
lntcoecd	0.446***	0.151*	0.315***	1.113***	-0.116
	(0.105)	(0.082)	(0.119)	(0.246)	(0.250)
lndist	-1.023***	-1.168***	-0.887***	-1.194***	-0.773
	(0.149)	(0.139)	(0.256)	(0.247)	(0.748)
comlang	0.354*	0.889***	0.542**	0.262	0.559
	(0.199)	(0.190)	(0.262)	(0.300)	(0.484)
colony	-0.403	0.253	0.447	-0.123	-2.838
	(0.260)	(0.214)	(0.352)	(0.344)	(3.038)
rta	0.622**	0.431**	0.434	1.055**	-0.387
	(0.248)	(0.213)	(0.372)	(0.471)	(1.385)
lngdpi	1.025***	0.679***	0.697***	1.062***	0.736***
	(0.055)	(0.195)	(0.049)	(0.125)	(0.074)
lngdpj	0.557***	0.528***	0.445***	1.071***	0.757***
	(0.066)	(0.184)	(0.046)	(0.179)	(0.083)
N	3,650	3,650	3,650	10,717	10,717
(Pseudo)R^2	0.386	0.577	0.316	0.238	0.033
Dummy Var.	Continent	-	-	Continent	-

Notes: Standard errors clustered at the country-pair level. One asterisk indicates significance at the 10% level, two asterisks indicate significance at the 5% level, and three asterisks indicate significance at the 1% level. A constant term is included in all regressions but the coefficient is not reported. In columns (1) to (3) the log of the amount of printers is the dependent variable, while in (4) and (5) it is the quantity itself. Columns (3) and (5) control for multilateral resistance with the Baier and Bergstrand (2009) methodology – each bilateral trade cost is included using the following formula: $\ln t_{ijt} + \frac{1}{N}\sum_{j=1}^{N} \ln t_{ijt} - \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} \ln t_{ij} + \frac{1}{N}\sum_{i=1}^{N} \ln t_{ijt}$. All columns include time dummies. Due to convergence problems of the PPML estimator were encountered when trying to estimate the equivalent to (2) with PPML.

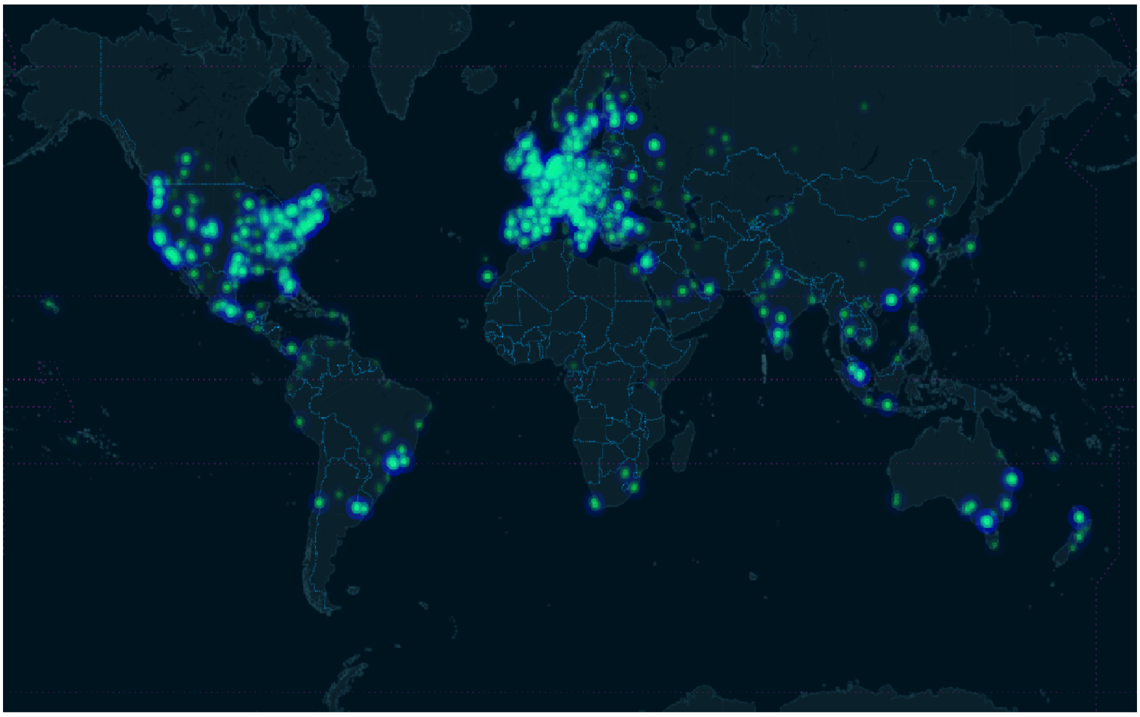

Figure 10: 3D printers registered in 3DHubs community as of May 2015

Source: 3DHubs

Table 7: Panel regressions with OECD transport cost measure (Chapter 90)

	OLS		OLS - BV	PPML	PPML - BV
	(1)	(2)	(3)	(4)	(5)
lntcoecd	0.412***	0.072	0.273*	1.014***	-0.313
	(0.108)	(0.096)	(0.141)	(0.243)	(0.299)
lndist	-0.912***	-1.122***	-0.850***	-1.047***	-0.663
	(0.155)	(0.143)	(0.254)	(0.256)	(0.665)
comlang	0.384*	0.876***	0.587**	0.357	0.473
	(0.197)	(0.185)	(0.256)	(0.314)	(0.442)
colony	-0.467*	0.251	0.374	-0.548**	-2.818
	(0.256)	(0.214)	(0.350)	(0.268)	(3.019)
rta	0.585**	0.408*	0.374	1.563***	-0.377
	(0.241)	(0.212)	(0.359)	(0.580)	(1.219)
lngdpi	1.024***	0.662***	0.712***	1.140***	0.740***
	(0.057)	(0.196)	(0.050)	(0.120)	(0.076)
lngdpj	0.586***	0.538***	0.442***	1.151***	0.754***
	(0.069)	(0.184)	(0.046)	(0.199)	(0.081)
N	3,639	3,639	3,639	10,308	10,306
(Pseudo)R^2	0.386	0.577	0.318	0.216	0.036

Notes: Standard errors clustered at the country-pair level. One asterisk indicates significance at the 10% level, two asterisks indicate significance at the 5% level, and three asterisks indicate significance at the 1% level. A constant term is included in all regressions but the coefficient is not reported. In columns (1) to (3) the log of the amount of printers is the dependent variable, while in (4) and (5) it is the quantity itself. Columns (3) and (5) control for multilateral resistance with the Baier and Bergstrand (2009) methodology – each bilateral trade cost is included using the following formula: $\ln t_{ijt} + \frac{1}{N}\sum_{j=1}^{N}\ln t_{ijt} - \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\ln t_{ij} + \frac{1}{N}\sum_{i=1}^{N}\ln t_{ijt}$. All columns include time dummies. Due to convergence problems of the PPML estimator were encountered when trying to estimate the

The use of Additive Manufacturing in the production process is more widespread and started earlier than the consumer use, as we have already mentioned in Section 1. Benson and Magee (2015) have analyzed several indicators based on patent data since 1976 and have identified 3D printing among the 4 most innovative technologies (out of a sample of 28). Although it is widely accepted that this technology is among the most path-breaking innovations, it is still unclear how widespread its adoption is. The reason is the scarcity of freely available data, with companies not willing to make their figures public, claiming that this will erode their advantages against potential competitors. According to a recent report by PricewaterhouseCoopers (2014) among almost two hundred firms surveyed in the US, around 66.7% of manufacturers are adopting 3D printing in some way, while almost 25% plan to do it in the future, and only less than 10% have no intentions of doing so. A similar report by Deloitte (2014) for Swiss companies reveals that 64% believe that 3D printing has the potential to be a key technology, although only 24% have already adopted it in some way.

The information collected from several reports and newspaper articles leads us to conclude that the main sector in which 3D printing has had a clear impact is medicine (especially for finished products or for important parts) and the automotive industry. For brevity, we will briefly discuss the medicine sector, but will especially focus on the case of the hearing aid industry.

4.2.1 Medicine

"3D printing is revolutionizing every aspect of the medical industry. It saves time and in turn more lives and also improves the efficiency of the surgery." Dr Muhanad Hatamleh, a senior clinical maxillofacial prosthetic at King's College Hospital, told IBTimes UK[14].

Several advances have been made in the medical and dental industry related to the use of 3D printing. The main applications can be classified into three broad categories (Ventola, 2014). These include: organ and tissue fabrication; pharmaceutical research on drug dosage forms, discovery, and delivery; and finally, creation of customized prosthetics, implants, and anatomical models. The main advantage of 3D printing as compared to traditional techniques is that it allows for customization and personalization, increases cost efficiency (ability to produce items at lower cost, regardless of the scale of production, reduces unnecessary resources), and enhances productivity (faster production times, higher accuracy, better resolution).

Wohlers Report 2014 (2014) describes that among the medical industry there are approximately 20 medical implants with clearance from the Food and Drug Administration (FDA), more than 90 thousands hip cup implants as well as implants to knee, spinal, and skull. More specifically, in the dental industry, more than 19,000 metal copings and around 17 million orthodontic aligners (which generate revenues of approximately half a billion of US$) are printed every day. The applications for bio-printing are also increasing

[14] `http://www.ibtimes.co.uk/3d-printing-medicine-how-technology-increasingly-being-used-save-lives-1502609`

in scope – network of capillaries have been already 3D printed (Ventola, 2014) and cosmetic companies such as L'Oreal are partnering with start-ups to produce human skin for testing [15].

4.2.2 Case study: Sonova/Phonak

An interesting case is the hearing aid industry, which has been using additive manufacturing for over a decade. Industry experts claim that over 10 million hearing aids have been produced by additive manufacturing. Among the main companies in the business, Starkey started using 3D printing already in 1998, while Phonak entered the market in 2000 (Sharma, 2013). Sharma (2013) states that the use of this technology has reduced the manufacturing process from nine steps to only three (scanning, modeling, and printing). Materialise[16] reports that 99% of the world's hearing aids are produced with Rapid Shell Modeling since 2000. The procedure has been greatly simplified over time and can be described as follows. First, an impression of the ear canal of the customer is taken by the audiologist. Next, this impression is sent to the hearing-aid manufacturer who creates the digital model[17]. Next, the shell is printed and manually postprocessed. Then the device is final assembled with all the necessary components like Electronic, Loudspeaker, Microphones. Finally, it is equipped with a removal line, and then lacquered for a high-tech finish. Concerning the time needed, "EnvisionTEC's printers can print 65 hearing aid shells or 47 hearing aid modules within 60 to 90 minutes"[18] and Starkey is able to sculpt and mold the final product in 24 hours (Sharma, 2013). Despite the fact that the technology is more efficient and reduces costs, only a few companies can afford the initial investments that this technology requires. In relation to the predictions of the theoretical model, Starkey, one of the leader firms, is engaged in foreign direct investment with over 30 printers operating across seven different production locations worldwide (Sharma, 2013). Moreover, we calculated some correlations with the one year lag of the sales of the industrial 3D printers (available for 17 countries) reported by Wohlers Report 2014 (2014) and the amount of hearing aids imported, as classified under the tariff line 9021.40.[19] Using data from 1992 till 2012, we observe a negative correlation of 0.13, which is statistically significant at the 10 percent level.[20] When we calculate the same correlation from the beginning of the period till 1999 (the year before 3D printing has been introduced in the industry) the statistical significance disappears. The same correlation for the subsequent period reaches a value of -0.17 and is statistically significant at the 5 percent level. This provides some support for the validity of the third prediction of our model.

[15] http://www.bloomberg.com/news/articles/2015-05-18/l-oreal-s-plan-to-start-3d-printing-human-skin

[16] http://www.materialise.com/cases/the-hearing-aid-industry-will-never-be-the-same-again

[17] Some audiologists can scan themselves the ear impression and send the data plus other ordering options such as Cerumen protection.

[18] http://www.forbes.com/sites/rakeshsharma/2013/07/08/the-3d-printing-revolution-you-have-not-heard-about/

[19] This tariff line not specific to the customized hearing-aids.

[20] The year 2013, although available, was excluded since Stratasys changed the headquarters to Israel and therefore results could be biased. The correlation is still statistically significant, though a bit smaller in size.

In order to get more detailed information on the adoption of 3D printing in the sector, we contacted Sonova (one of its brands is Phonak) – another industry leader. Their adoption of 3D printing (already by the beginning of the new millennium) is very impressive – almost all of the shells for the custom-made in-the-ear hearing aids are produced using additive manufacturing. With the same technology they produce several Custom Earpieces for Behind-The-Ear and Receiver-In-Canal hearing aids. This technology adoption significantly reduced the time needed and the production costs and in a reproducible process across company's locations. The company states: "Phonak is able to mass-produce hundreds of thousands of custom-made products with high precision, at multiple sites across the globe and in a great quality, year by year". Their technology allows them to produce up to 40 shells when using the EnvisionTec Perfactory III printer, with a printing time of circa 80 minutes. Some advantages of the technology – among many others – are fast turn times, an environmentally friendly process with a safe working environment and a group-wide unique process that provides the customer with the same product quality independent of his/her geographical location. An interesting aspect of the company is that Sonova has different manufacturing sites (using 3D printing) across the globe. They have one facility in Latin America, three in North America, five in Europe, three in Asia and two in Oceania. Two of the newest facilities from the aforementioned company were opened in Asia and one in Latin America. This case study serves as an excellent example to illustrate the predictions obtained in the theoretical section. For instance, only the most productive firms are using the newest technology (3D printing) and are already engaged in FDI in different locations across the world. Moreover, the markets they serve are characterized by a high demand – either Europe, North America, Oceania or the specific locations in Latin America and Asia.

To summarize, while in the previous subsection the empirical evidence supported the first hypothesis, the presented company level anecdotal evidence is in line with the second prediction of the model, while the aggregate macro-level evidence would be in favor of the third one.

5 Conclusions

This paper is the first attempt to analyze the evolution of 3D printing techniques and trade in 3D printers in relation to globalization from a theoretical and an empirical perspective. Certainly, 3D printing is still in its infancy and a high degree of uncertainty will most likely influence the future impact of this path-breaking technology on production relocation and trade. The product life-cycle-type theory presented in this paper indicates that the wider adoption of 3D printing in industrial processes around the world could eventually lead to "glo-calization" (shipping parts and components internationally becoming less important), a force that could probably counteract the ongoing globalization trend. Although the time frame in which these changes will happen is uncertain, there is surely going to be a progressive change in the way in which some products (e.g. automobiles, airplanes, and medical related) are manufactured. The economic, social, environmental, and security implications deserve to be investigated by economists, social scientists, lawyers, and engineers.

The results obtained in the empirical analysis confirm the first prediction of the model. Countries with higher GDPs that are subject to higher transport costs are indeed trading more 3D printers. The case study presented provide suggestive evidence on the second and third predictions of the model. 3D printing FDI seems to be replacing traditional FDI as well as international trade. Further research to extend the empirical analysis will only be possible when more data becomes available for the research community. Extensions that are worthwhile to consider for future research are to incorporate into the theoretical model the benefits of customization that this technology allows for, as well as to analyze the relationship between the adoption of 3D printing and the associated impacts on the labor market.

A Appendix

A.1 3D printing classification description

The first step to identify the classification of the printers was to search in the Harmonized System classification (HS) of the World Customs Organization and of the different countries. Since the wording "3D printers" has not yet been included in the classification systems, is it impossible to uniquely identify the exports and imports of these items. The last revision of the HS was made in 2012 and surprisingly, there were no new entries concerning 3D printers and related products. According to a legal case related to 3D printers' classification, Hodes and Mohseni (2014, p. 46) state that "neither the importer nor the government may be entirely certain of the correct classification". The only information that we were able to find from an official governmental source that actually includes "3D printers" in the tariff schedule was for Hong-Kong and its reported 2014-HS revision. We also searched within the latest national tariff schedules of a number of countries, namely China, Japan, India, Singapore, and Canada and no specific tariff line for 3D printers was found. Therefore, to shed some light on this issue and to investigate under which tariff lines do the countries and firms classify trade in 3D printers, we conducted a fieldwork investigation. By means of telephonic interviews and emails we were able to collect information for five countries that is summarized in Table A1. The main findings indicate that the same items are being classified under different headings when exported from different countries. There are even disagreements within the same country (Argentina; US) or the same custom's union (Germany and Spain), although in some cases 3D printers could differ in the type of material they use as an input and this could lead to a different classification of exports. However, in other cases, printers using the same material were also classified under different headings.

Country	Code	Source	Material
Argentina	3909.50.19	Trimaker	Plastic (cartridge)
Argentina	8477.20.10	Kikai Labs	Plastic
Argentina	8477.80.90	Trimaker	Plastic
Hong Kong	8477.59.10	Trade and Industry Department of Hong Kong (http://www.tid.gov.hk/english/cepa/tradegoods/files/mainland_2014.pdf)	Plastic
Germany	8474.80.90	German Federal Statistical Office	Minerals /metals
Germany	8477.80.99	German Federal Statistical Office	Plastic
Spain	8443.32.10.90	SICNOVA3D and Valencia Port authority	-
United States	8477.90.8595	Flexport http://learn.flexport.com/import-3d-printers	Plastic (cartridge)
United States	8477.80.0000	Flexport http://learn.flexport.com/import-3d-printers	Plastic
United States	8477.59.01.00	U.S. Census Bureau - Foreign Trade Schedule B (2015) (https://uscensus.prod.3ceonline.com/)	Plastic
United States	8477.80.00	Hodes and Mohseni (2014)	Plastic
United States	8479.89.98	Hodes and Mohseni (2014)	Metals

Table A1: Collected information (from January 2015 till June 2015) on tariff lines considered for the trade of 3D printers

According to Table A1, the 6-digits HS codes (tariff lines) considered in these countries for the trade of 3D printers is 8477.80 from the HS (2007 revision). Germany and the United States classify exports of 3D printers that work with plastic or rubber under code 8477.80[21], whereas Spain (which – as Germany – belongs to the EU, a customs union with a common trade policy) classify trade in 3D printers under code 8443.32. This code was also suggested by the popular website "Duty Calculator" for the item "3D Printers"[22]. The same website suggests that the classification of the printers (working with laser) produced by EOS is 8456.10 [23]. In Argentina, two companies that were interviewed reported the use of different codes. Kikai Labs used 8477.20, whereas Trimaker reported trade under the code 8477.80. Given the description of the tariff line (see Table A2), this could be because

[21] When we initially consulted the website of Flexport on February 2015, they recommended to use the tariff line 8443.32.1090 for printers working with plastic.

[22] http://www.dutycalculator.com/hs-lookup/423051/hs-tariff-code-for-3d-printer/, accessed on February 2015.

[23] http://www.dutycalculator.com/dc/190714864/business-industrial/industrial-agricultural-machinery/laser-cutting-machine/import-duty-rate-for-importing-eos-additive-manufac 4/, accessed on July 2nd 2015.

Kikai produces printers that can print small objects. Finally, we have only two entries in Table A1 for which we know that the 3D printers work with metal or mineral inputs, one for the US and one for Germany and once again the reported codes differ. The code reported by Germany was 8474.80.90, while the US reported the use of code 8479.89.98.

Country	Code	Description
Most common 6 digits	8443.32	Other printers, copying machines and facsimile machines, whether/not combined , excluding the ones which perform two/more of the functions of printing, copying/facsimile transmission; capable of connecting to an automatic data processing machine to a network
Most common 6 digits	8477.80	Machinery for working rubber/plastics/for the manufacture of products from these materials, not specified /incld. elsewhere in this Ch., Other machinery, n.e.s. in 84.77
Argentina	3909.50.19.000A	Amino-resins, phenolic resins and polyurethanes, in primary forms. Plastics and articles of plastic; Polyurethanes; others
Spain	8443.32.1090	Other, capable of connecting to an automatic data; Printer units; Other
Argentina	8477.20.10	Machinery for working rubber or plastics or for the manufacture of products from these materials, not specified or included elsewhere in this Chapter; Extruders; for thermoplastics, with a screw diameter not exceeding 300 mm
United States	8477.59.01.00	Machinery for working rubber or plastics or for the manufacture of products from these materials, not specified or included elsewhere in this chapter, parts thereof; other machinery for molding or otherwise forming; other
Hong Kong	84775910	Three-dimensional printer (3D printer)
United States	8477.80.00	Machinery for working rubber or plastics or for the manufacture of products from these materials, not specified or included elsewhere in this chapter, parts thereof; Other machinery
Germany	8474.80.90	Machinery for sorting, screening, separating, washing, crushing, grinding, mixing or kneading earth, stone, ores or other mineral substances, in solid (including powder or paste) form; machinery for agglomerating, shaping moulding solid mineral fuels, ceramic paste,unhardened cements, plastering materials or other mineral products or in powder or paste moulds of sand;other form; machines for forming foundry machinery; other
Argentina	8477.80.90.000W	Machinery for working rubber or plastics or for the manufacture of products from these materials, not specified or included elsewhere in this Chapter;other machinery; other
Germany	8477.80.99	Machinery for working rubber or plastics or for the manufacture of products from these materials, not specified or included elsewhere in this chapter;other machinery;other
United States	8479.89.98	Machines and mechanical appliances having individual functions, not specified or included elsewhere in this chapter; parts thereof; Other: Electromechanical appliances with self-contained electric motor;Other

Table A2: Collected information on tariff lines considered for the trade of 3D printers with description

A.2 Summary Statistics

Table A3: Summary Statistics: cross-section

Variable	Mean	P50	S.D.	Min.	Max.	N.
lnquan	3.522	3.367	2.424	0.000	10.110	359.000
lntcoecd84	-3.590	-3.455	0.790	-6.571	-0.941	856.000
lntcoecd87	-3.585	-3.464	1.009	-6.166	-0.835	755.000
lntcoecd90	-3.931	-3.740	0.938	-7.601	-1.099	714.000
lnfedex (25kg)	7.015	7.019	0.373	4.690	7.569	207.000
lnfedex(1kg)	5.014	5.061	0.217	4.293	5.364	211.000
lndist	9.050	9.161	0.553	5.371	9.892	856.000
comlang	0.123	0.000	0.328	0.000	1.000	856.000
colony	0.027	0.000	0.162	0.000	1.000	856.000
rta	0.137	0.000	0.344	0.000	1.000	856.000
lngdpi	26.751	26.721	1.785	21.819	30.451	856.000
lngdpj	27.216	26.659	1.636	24.743	30.451	856.000

Table A4: Summary Statistics: panel

Variable	Mean	P50	S.D.	Min.	Max.	N.
lnquan	3.180	2.890	2.351	0	12.554	3894
lntcoecd84	-3.457	-3.350	0.790	-8.517	-0.223	12531
lntcoecd87	-3.343	-3.163	0.981	-8.517	-0.173	10717
lntcoecd90	-3.762	-3.654	0.941	-9.210	0.141	10308
lndist	9.074	9.183	0.568	5.371	9.892	12531
comlang	0.131	0	0.338	0	1	12531
colony	0.027	0	0.162	0	1	12531
rta	0.053	0	0.224	0	1	12531
lngdpi	26.166	26.219	1.893	20.359	30.451	12531
lngdpj	26.627	26.292	1.844	22.793	30.451	12531

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