Cross-border and domestic early-stage financial investment in the 3D printing ecosystem: An empirical perspective on drivers and locations

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Abstract

3D printing is a relatively new digital technology which can transform the way firms organize their innovation and production operations locally and globally. Whilst 3D printing is being adopted by diverse organizations worldwide, empirical academic research on investment in early-stage 3D printing technology firms is still limited. In this paper, we consider the geography of the 3D printing ecosystem to illuminate the financing of investment into early state firms developing innovation in this technology. Using a hand-collected dataset of 500 firm-level investments, we hypothesize 3D printing investment is drawn to countries with greater innovative capacity, countries with greater human capital competencies, and countries with higher wages. We find that larger investments tend to benefit companies developing 3D printing technology in higher wage locations and in countries with higher innovative capacity level, suggesting that investments in the 3D printing ecosystems take places mostly in locations that already have an ecosystem in place. Our study is one of the first to examine detailed patterns of global investment in a new digital technology ecosystem - 3D printing, an increasingly important technology for innovation.

Keywords: additive manufacturing (AM), 3D printing, international investment, innovation technology, Industry 4.0, international business

1. Introduction

In the last two decades, digitization and the increasingly low cost of the internet had facilitated the relocation of business services to offshore locations (e.g., Dossani and Kenney, 2007), thus leading to the reconfiguration of global value chains (Laplume et al., 2016), increasing adoption of offshore outsourcing and the emergence of a strong business service providers industry (e.g., Manning et al., 2018). The recent improvement of technologies that are grouped under the framework of Industry 4.0 – which include augmented reality, the industrial Internet of Things, autonomous robots, big data, cloud computing, artificial intelligence, digital platforms, robotics, and additive manufacturing (Rose et al., 2016; Menon et al., 2020; Huber et al., 2022), - are transforming production and innovation processes. The development of 3D printing technologies has played a strong role in the reorganization of innovation and production, and altering their geographical configuration (Laplume et al., 2016; Ciarli et al., 2021).

Research has studied the impact of adopting additive manufacturing and internationalization of production (e.g., Laplume et al., 2016; Strange and Zucchella, 2017; Autio et al., 2021; De Beule et al., 2022). However, there is surprisingly little academic empirical modeling research on the development of these technologies, including the international geographical configuration of investment in 3D printing technology, especially considering that financial constraints are a well-acknowledged limit to the development of new technologies.

We conceive 3D printing technology as modular and constituting an innovation ecosystem which comprises the evolving set of actors, activities, and artifacts, and the institutions and relations (Granstrand and Holgersson, 2020) such that investment in innovation can occur at various 3D printing-related components or modules, architecture, materials, software, implementations, applications, electronics, and so on, which in principle can be located and invested in anywhere. Scholars have long explored the factors that contribute to decisions by firms to invest in specific geographic locations in response to resource or other attributes of those localities (Hahn et al., 2009). The disruptive nature of 3D printing, however, may contradict conventional assumptions about the drivers of investment and lead to new insights regarding the locations of these financial investments. This is because specific country characteristics, e.g., economic, financial, technological, and human capital, that is, the diverse components of a technological eco-system, are likely to attract investment in this new technology, affecting the dominance of countries, and companies in these countries, in the global landscape (Ahi et al., 2022). Therefore, a number of questions can be raised: where are early-stage 3D printing technology firms and 3D printing investors located? Do investments move cross-border, or do they tend to stay within national boundaries? Considering that the most successful companies in the 3D printing industry could serve global demand, from an investor point of view, does the location of early-stage firms in the 3D printing ecosystem matter, or does it not, as they will be able to tap into a potential global market and export their products anywhere?

In this paper, we examine the geography of technological eco-systems in relation to a particular technology – 3D printing – through early-stage financial investments into firms developing 3D printing technologies in an attempt to identify and understand the role of country drivers and locations characteristics (such as innovation infrastructure and availability of human capital) on investments in 3D printing technologies as a coevolutionary dynamics, that is, we investigate whether investments tend to be located in those locations where there are already elements of an emerging eco-systems. Such investments, in turn, will contribute to further development of the technology ecosystem. We investigate the role of investments to support the development of this technology in stimulating such ecosystems in specific locations.

We hypothesize that some of the factors that often drive cross-border investments in other sectors, such as lower wages, may be less impactful or even irrelevant in the case of 3D printing and its value ecosystem, while, at the same time, factors such as innovation support and an overall environment conducive to innovation are likely to be more important. Due to the ability of 3D printing to reduce the development cost and time for new products, the attraction of a low labor cost location will diminish. Instead, companies will be freer to locate where they wish to develop, and adopt, 3D printing technologies, and this may often be in a high labor cost location. All of these factors align to make high labor cost locations more attractive than they were previously, and we argue this motivates larger investments in those locations, thus fostering emerging ecosystems. We test our hypotheses on an original data set of 500 firm-level financial investments into innovative early-stage firms in the 3D printing ecosystem worldwide. We find that larger investments are made into 3D printing companies in higher wage locations, that cross-border investments predict larger investments, and that other aspects of the investment destination (such as higher human capital level) also affect this process.

In the following section we provide a brief background on 3D printing to illustrate its transformative impact on the innovation and production processes, as well how the technology is still experiencing a rapid pace of development and that it remains open to substantial technological progress and innovation. Then, we elaborate on the main issues around the location for cross-border versus national investments in 3D printing discussed in the literature, which lead to the formulation of four hypotheses. Next, we present the data for the empirical tests of the hypotheses, explaining in detail the collection of original data about investments in 3D printing and the supplementary secondary data used for the hierarchical regression models. This is followed by a brief discussion of the methods used and the presentation of the results. The paper ends with a concluding section presenting a discussion of our findings and managerial implications, limitations and suggesting avenues for future research.

2. Investing in 3D Printing: Literature and Hypotheses

The next section aims to provide a brief overview of the technology as background for the study which focused on the investment in 3D printing innovation. We then continue by presenting research pertinent to the specification of our hypotheses.

2.1 Background on 3D printing

3D printing is a type of additive manufacturing whereby objects are constructed through the bonding or joining of materials. It differs from many conventional manufacturing techniques which are subtractive, such as cutting and lathing. Many materials, such as metal, plastics, polymers, and food ingredients, are widely available to firms seeking to leverage this technology in their production processes. As a result, 3D printing has been identified as a disruptive technology (Rayna and Striukova, 2016). For example, the U.S. Marines have described 3D printing a part for the F-35 stealth fighter which led to a cost savings of $70,000 (Iftikhar, 2018). The fighter jet's part, which had broken, could not be purchased separately from the supplier. The Marines were able to reverse-engineer, design and manufacture the part themselves in the field without having to go through a lengthy and expensive procurement. Elsewhere a neighborhood of 100 3D printed homes is slated for construction in Austin, Texas in 2022 (Listek, 2021), disrupting the conventional construction industry.

Hence 3D printing has attracted industry interest, due to its capability for supporting innovation, new product design and development, and dramatic design improvements, while simultaneously reducing many kinds of costs and decreasing manufacturing times (Rayna and Striukova, 2021). Although the early development of 3D printing technology traces back a few decades, it is still at a somewhat early stage of technological development toward more widespread adoption and diffusion, with substantial innovation opportunities in printers, materials, and software, which continues at fast rates. Companies developing 3D printing technologies are investing in new designs and new materials, for both industrial and domestic use. 3D printing is used in manufacturing, for new product development, design and prototyping and small-scale production, and in supporting and complementing large scale production, which uses other Industry 4.0 digital technologies (e.g., artificial intelligence-controlled robots). While most authors agree that 3D printing represents a radical innovation, Steenhuis and Pretorius (2017) provide a noteworthy and nuanced perspective. They observe that 3D printing is not a monolithic entity – rather 3D printing's impact differs across the various components of the ecosystem: applications, materials, design, equipment manufacturing and services (Xu et al., 2018). Furthermore, Steenhuis and Pretorius (2017) point out that the same activity may be more or less disruptive depending on the circumstances of the production processes where it could be implemented. Finally, 3D printing may be differentially profitable in different locations, a topic we examine next.

2.2 Investment and location decisions

Early stage of development of new technologies presents substantial financial risks as well as opportunities for future large profits from successful development of the technology. Investors seek to put capital to work to generate profit, therefore they will structure their investments so they continue when profits are expected; conversely, they will exit their investments when costs outweigh profits (Cumming and Johan, 2010). Except for a few notable giants such as Stratasys, most firms specializing in developing 3D printing technology are small sized due to the still-emerging nature of the technology and/or to the insightful application of its capabilities to previously unmet or unrecognized business needs, thus presenting opportunities to smaller, entrepreneurial firms who aspire to find a place in an industry dominated by few incumbents (Steenhuis and Pretorius, 2017). These smaller firms are less likely to be able to directly access public equity markets and will therefore need to satisfy their funding requirements from venture capital or angel finance (Berger and Udell, 1998; Gregory et al., 2005).

Venture capital firms and angel finance providers that specialize in high-tech small business funding may look anywhere in the world to invest (Cumming and Johan, 2010; Devigne et al., 2013). But where do these investors in small business funding prefer to invest?

For decades, scholars have explored the home and host-country factors influencing cross-border investment. Despite attractive investment opportunities being spread throughout the globe, often investors prefer to invest nearer to home (Robinson and Cottrell, 2007; Guenther et al., 2018). French and Poterba (1991) found that US citizens had over 93% of their equity portfolios invested in US equities, while Japanese citizens had over 98% of their equity portfolios invested in Japanese equities. Tesar and Werner (1995) obtained similar findings, but also found that investors who did invest abroad had more turnover in their foreign investments than they did in their domestic investments. Tesar and Werner also observed some international heterogeneity in willingness to invest abroad; investors in some countries (such as the UK) were more willing to invest abroad than were others. Ke et al. (2010) found that the home bias persisted even after controlling for a firm's international involvement and its worldwide visibility. This may be due to top management being present in and more oriented toward the home country. Coval and Moskowitz (1999) found that 1 out of 10 firms in a U.S. money manager's portfolio is chosen because the manager is located in the same city as the firm. They found that the home bias extends to international investing as well. For example, US investors were overweight Canadian equities versus investors from Europe or Japan. The home bias phenomenon for investment is puzzling because presumably investing managers should be pursuing larger returns wherever they may be found globally. In addition, investing managers have advanced research tools and access to large databases of global corporate and investment performance data for the purposes of increasing returns, so geography might not be expected to matter.

Despite this, many firms prefer to invest locally due to greater familiarity (Huberman, 2001) and ease of acquiring information. Ease of acquiring information may be especially important for 3D printing investments because 3D printing is an emerging area where new developments and disrupting innovations arise often. Bernile et al. (2015) indicate that local investment may be especially prevalent when firms are hard to value. This characteristic may apply to many of the firms in the 3D printing industry because the industry itself is in an earlier phase of the industry life cycle (Vernon, 1966; Hofer, 1975; Klepper, 1997), and investment capital may not be seen to cross international borders as often as in the case of a more mature phase. However, more recently, the amount of cross-border investments has been growing (Wright et al., 2005; Guler and Guillén, 2010; Aizenman and Kendall, 2012; Chemmanur, Hull, and Krishnan, 2016), and the prevalence of foreign venture capital (VC) investment has been increasing. Investors are increasingly considering foreign locations for their ventures as a way of expanding their portfolios and options, and foreign businesses, especially in emerging economies, welcome international investors due to their experience in advising entrepreneurial ventures, providing product market support, professionalizing firm management, setting effective incentive schemes, and through monitoring firm management. Foreign VCs possess institutional knowledge about foreign markets that can help the internationalization of portfolio companies, and possess foreign business knowledge about suppliers and customers that support portfolio companies' international activities (Chemmanur et al., 2016).

When international investments are made, they may have outsized benefits to the recipient firm. Ferreira and Matos (2008) described that firms with a greater proportion of foreign ownership tend to have higher valuations and better operating performance. Ferreira and Matos argued that this may be due to the foreign investor taking a more active role in monitoring the local recipient. Foreign managers may be more likely to intervene in the recipient firm to ensure shareholder value, or else to exit and take their footloose capital elsewhere. Aggarwal et al. (2011) extended this finding by showing that investors from countries with strong shareholder protections have a positive influence on corporate governance when they invest in international firms.

3D printing has innovation-based characteristics that may suggest a different or more specific set of conditions that would make a given location especially attractive for investment in this new technology (Si et al., 2023). 3D printing permits relatively rapid prototyping. Many designs can be fabricated with 3D printing within hours or days of their creation, compared to the weeks or months that conventional manufacturing methods may require. 3D printing also supports just-in-time inventory strategies because, when a design is needed, it is printed on demand. This greatly reduces material costs (Kayikci et al., 2022) as well as warehousing demands and inventory costs (Heinen and Hoberg, 2019). 3D printing also compares favorably when only a small volume of a product is desired. Most conventional manufacturing techniques require large economies of scale for financial viability.

Due to the transformative nature of 3D printing technologies in manufacturing, through the reduction of the number of production stages and, by and large, the advantages in economies of scale, companies may be further rethinking the organization and the location of their innovative and manufacturing activities. The advantages of 3D printing are expected to alter location strategies and investment decisions by both innovators in 3D printing and external investors in the technology.

While the literature on 3D printing ecosystems is still growing, in our review we could not find research on investments into early-stage firms in the 3D printing industry. The relationship between 3D printing and various dimensions of the entrepreneurship process are still relatively underexplored (Rayna and Striukova, 2021), a critically important topic which is the focus of this paper. Ultimately 3D printing is a relatively newly popular manufacturing technique with a unique array of value propositions.

It remains an open question as to which aspects of the value propositions – costs, innovation environment, and human capital – are most attractive to investors who are risking their own large sums of money in this uncertain period of manufacturing technological evolution. The specific institutional setting of different countries has been recognized as relevant factor affecting investment decisions in support of innovation activities by high-tech entrepreneurial firms (Corsi and Prencipe, 2019). However existing research on small and medium-sized enterprises (SMEs) with respect to Industry 4.0 topics such as 3D printing and the Internet of Things remains limited (Wasim et al., 2022). We have therefore cast a broader net to elaborate hypotheses regarding country-level factors influencing the location of investment decisions into 3D printing SMEs.

2.3 Hypotheses

Below we generate our hypotheses after summarizing relevant literature and describing our theoretical perspectives.

2.3.1 Labor costs

Historically manufacturing has been inclined to migrate to locations with lower comparative costs (Lösch, 1954; Woodward and Rolfe, 1993; Amirahmadi and Wu, 1994; Gerybadze and Reger, 1999, with some notable exceptions, see Ketokivi et al., 2017). Hence, recent decades have seen an acceleration in the use of offshoring of manufacturing as well as business services, including high value adding activities such as R&D, engineering services and product design (e.g., Bunyaratavej et al., 2007; Lewin et al., 2009). Sethi et al. (2003) found that low wages were incentivizing US firms to enter Asian markets in the years preceding the 2000s. The tantalizing prospect of reduced costs and lowered wages in conjunction with maintaining retail prices largely constant can be a compelling value proposition. Similarly, companies located in high-cost western countries have been offshoring business services to emerging countries where they could benefit from relatively low-cost talent and skilled workers for high value adding tasks and activities (e.g., Lewin et al., 2009). However, over time, some of the cost advantages have been eroded by wage inflation in hot spot locations in countries like India and China, consequently a more nuanced view of offshoring emerged when expected value propositions did not always materialize. This led to research reconsidering new global sourcing trends and factors explaining them. For example, Bals et al. (2016, p. 102) noted 'managers are increasingly reconsidering some previous outsourcing and offshoring decisions causing them to revoke some of these'. In revoking these decisions, managers may elect to move business services closer to the home country but not within it (i.e., nearshoring), or alternatively, they may choose to relocate production back within the home country (i.e., reshoring or backshoring) (e.g., Albertoni et al., 2017).

About the location of high value creation activities, such as R&D for the development of 3D printing technologies, it has been argued that such activities tend to be located in high-cost locations (e.g., Rungi and Del Prete, 2018). Moreover, since 3D printing can shorten the innovation and product development process and since it allows for product customization, it can lead to various activities related to the development of the 3D printing ecosystem being located in proximity. Because the human element of creation and vision are essential to new product development, creative as well as technical skills play critical roles in additive manufacturing just as in conventional manufacturing. Advanced skill sets are needed to envision, design and produce high value-adding products (Gress and Kalafsky, 2015). A managing director at UK manufacturer William Cook relates 'Commodity parts are routinely sourced from low-cost economies against which William Cook finds it difficult to compete on price. So, William Cook concentrated on high added value, high integrity, and high difficulty and niche products. These require the use of state of the art and cutting-edge technologies supported by a highly skilled workforce' (Jackson, 2017).

Therefore, it is likely that the developers of 3D printing technology would be located in places where there is availability of skilled (and costly) advanced workers/developers/researchers, who are also able to support the firms' adoption of the technology (and, all in all these high-wage locations tend also offer innovation infrastructure and advanced human capital resources, which we will discuss next) Although location of 3D printing would not matter for its adoption for manufacturing, we argue that it matters for the development of the technology and benefitting from being located within ecosystems which include availability of highly paid employees and researchers. Thus, we argue that investments in developing 3D printing technology within its ecosystem are more likely to occur in high wage locations and propose the following hypothesis:

H1: The higher the wages in a country, the larger will be the investments into early-stage 3D printing ecosystem companies in that country.

2.3.2 Country-level innovation environment and country-level human capital

A country's innovation activities are normally supported by national formal and informal institutions that directly and indirectly affect innovation capabilities (Freeman, 1987; Nelson, 1993). Innovativeness among employees and an innovative corporate culture are important intellectual resources a firm may possess (Froehle and Roth, 2007). In terms of deciding where to invest, VCs are likely to consider innovators in 3D printing located in places highly conducive to the successful development of new products, as well as suppliers and consumers who could be directly involved in the development and design of innovations. This is in part because innovative activities can be positively influenced by proximity and clustering effects (Leszczyńska and Khachoul, 2018).

The development of new 3D printing technologies requires both hard knowledge in terms of patent applications, high-tech exports, and creative goods and services production, as well as softer skills for both developing and adopting 3D printing technologies (Steenhuis et al., 2020). A related concept (but one that is distinctly delineated in the literature) is the presence of human capital. The relationship between business success and human capital has been extensively examined and documented; for example, Unger et al. (2011) performed a meta-analysis on 70 research studies performed over a three-decade period on this topic, finding it to be a robust and far-reaching phenomenon. The importance of human capital in 3D printing was assessed by Yeh and Chen (2018) in terms of 3D printing adoption at the firm level. Yeh and Chen found organizational factors such as human capital were judged to be third in importance. In related work, Mellor et al. (2014) described workforce experience levels and skill as being among the key factors for the implementation of additive manufacturing, suggesting that the presence of better human capital offers a favorable environmental condition for the development and the adoption and implementation of 3D printing. Hamalainen and Karjalainen (2017) and Troxler and Wolf (2017) provided multiple case studies of small-business entrepreneurs who innovated business models using 3D printing. These case studies demonstrate the importance of technical skills as well as soft skills such as proactiveness, mental agility and adaptiveness, and the ability to identify and commercialize trends to respond to local and online market needs.

Given the salience of the innovative national environment in terms of overall innovation performance (e.g., patent applications, high-tech exports, and creative goods and services production), as well as a country's human capital (e.g., learning, education, skills and employment levels) in the successful development and adoption of 3D printing (and business success more broadly), we propose the following hypotheses:

> H2: The higher the level of innovation infrastructure in a country, the greater the investment amounts into early-stage 3D printing ecosystem companies will be.

H3: The more advanced the human capital in a country, the greater the amounts of investment into early-stage 3D printing ecosystem companies will be.

2.3.3 International versus Domestic Investment

As discussed earlier, there are two countervailing trends regarding national versus international investment. On the one hand, a major research stream (originating with Martin and Rogers, 1995) shows that capital is footloose and has the ability to cross borders in search of higher returns. On the other hand, many investors and investing firms may concentrate their investments in their native location due to greater familiarity. It may be that larger and more strategically valuable investments attract international attention and investment. Especially high value propositions may induce capital to be more footloose and flow more readily across borders. Due to increased interest from deep-pocketed investors, local investors may be crowded out. Conversely investment opportunities with less potential may fail to make much of an impact in the attention marketplace (Webster, 2014). These investment opportunities may therefore only attract the attention of local investors. These local investors may not be among the most deep-pocketed investors in the world. As such, we might expect a trend toward smaller investments arising from local/domestic investors.

The empirical literature on investment trends in 3D printing is currently sparse. To the best of our knowledge, there is no published empirical modeling research to date that focuses on both international and domestic investment in 3D printing, nor is there research involving early investment (pre public offering) into smaller 3D printing firms. A recent closely related work is Goldberg et al. (2022), who examined stock market impacts of firm announcements of investments into 3D printing. In particular they examined 84 instances of publicly-traded firms that announced investments into 3D printing during the period 2011-2017 using data from Factiva, the NYSE and the NASDAQ. As mentioned, stock market response to these announcements was context-dependent. Elsewhere Buonafede et al. (2019) found a country-level negative relationship between patent activity in additive manufacturing and participation in global value chains, suggesting that firms are more likely to focus domestically versus abroad for their innovation activities in additive manufacturing. Following the literature on international VC investments, we do expect variation in the mix of domestic versus international sources of investment in 3D printing; however, existing theory is not specific to 3D printing and is somewhat equivocal.

As described in Section 2.2, on the one hand investors might prefer to invest larger sums in their own countries, as they are more familiar with local institutions and regulations, possess better knowledge of the local innovation and human capital endowments, and the geographical proximity allows them to follow and support the recipient companies more closely. On the other hand, financial investors are attracted by high return opportunities and these may not be in the investors' home country. Hence some investors will be willing to consider foreign locations and companies, as the market for 3D printing technologies is not limited to domestic buyers but is potentially global. Therefore, the financial returns of an investment on developing an advanced and competitive technology are likely to produce high returns to their investments, regardless of the location. This also suggests that international investments in 3D printing would tend to be larger than intra-national investments in 3D printing. Therefore, since prior literature presents arguments in favor of both domestic and foreign investments, we propose the following two opposite hypotheses:

H4a: Investors tend to invest larger sums when they invest into early-stage 3D printing ecosystem ventures domestically.

H4b: Investors tend to invest larger sums when they invest into early-stage 3D printing ecosystem ventures in foreign countries.

3. Data, Methods and Results

In this section we describe our data and review the statistical models that we use to test our hypotheses. We then describe our results.

3.1 Study Data

In the following sections we discuss our dependent and independent variables. We also discuss the data acquisition as well as the cleaning process.

3.1.1 Financial Investments

The dependent variable for this research is the amount of money (converted to US dollars) invested by one party into a second party, where the second party is an early-stage firm in the 3D printing industry ecosystem (Beltagui et al., 2020; Strange et al., 2022). To find this information, we searched the site 3DprintingIndustry.com for news articles containing financial investment information complemented with Crunchbase, a platform that is known for a focus on technology-oriented start-up firms. Since there is no universal dataset consisting of the entire population of firms in the 3D printing ecosystem, we referred to what appear to be the two best available sources for the purpose of the study. 3DprintingIndustry.com is an online website which reports on and aggregates publicly available news regarding the 3D printing industry. 3DprintingIndustry.com has a worldwide geographic scope and its advertising-based business model is likely an incentive for it to have timely and reasonably comprehensive coverage of important events in the industry. All articles containing the key words ‘investment’ were obtained in one pass, all articles containing ‘invested’ were obtained in a second pass, and all articles containing 'investing' were obtained in a third pass. This led to 1521 article URLs being obtained, 235 of which were duplicates since any article which contained more than one of the keywords would appear more than once in the total. It was straightforward to de-duplicate these by sorting by URL and removing duplicates. All URLs were obtained within a 48-hour period in late January 2018.

The data extraction was performed by the first author. Articles were read to see whether one party was described as making a financial investment into a second party, whereby the second party was a firm in the 3D printing industry. In some articles, the keyword(s) was used in a non-financial way ('we are investing in our future' or 'Person X invested a lot of time in Y'). These articles were tagged as no actual investment and discarded. Given the large number of articles, coding instructions were created, and two undergraduate students and a retired business executive were asked to process a small number of articles to check if the task was doable and the instructions were clear. The task was then contracted out to a professional data entry firm. Random quality assessments performed as the data arrived revealed that the professional was assessing the articles correctly and the investment amounts and business names were being entered exactly. Occasional minor corrections were needed with geographical data such as changing a Country variable that was coded as 'Dubai' to 'United Arab Emirates' or 'Scotland' to 'United Kingdom'. The process was then repeated in subsequent years to obtain data from 2019 and 2020 following exactly the criteria previously described. This resulted in our having a total of 214 observations from 35 countries from 3DprintingIndustry.com). Each of these 214 observations documents a firm-level dyadic event involving an investing firm and a separate investment recipient firm. Virtually all investments retrieved from 3DprintingIndustry.com are for technology development; some investments support a combination of technology and business development/expansion, often with the support from high-tech VCs who are investing in them. Only a handful of investments are solely about commercialization and business expansion, still contributing to the development of the 3D printing ecosystem.

To complement the data from 3DprintingIndustry.com and reduce possible issues arising from the use of a single data source, we then broadened our data sources to use the data source Crunchbase. Crunchbase is a platform that is known for a focus on technology-oriented start-up firms (see, for example, Croce et al., 2018) and can identify activities in the industry involving small entrepreneurial new entrants which might have been overlooked by the specialized 3DprintingIndustry.com. We screened for firms on Crunchbase that were categorized by Crunchbase as being in the 3D printing industry category and that had received a financial investment during the time period January 1st, 2013 through December 31st, 2020. The beginning of this time period was selected to approximately correspond with the beginning of the time period of the data collected on 3DprintingIndustry.com, which had only two observations in the year 2012 and none prior to 2012.

This data was then examined to ensure that geographic information was available for both the investing firm and the recipient firm. Crunchbase provides information on both lead investors and other investors. If a particular investment was associated with a lead investor, we coded investment as originating based on the geographic information on the first lead investor as given on Crunchbase. If this was not available, we coded investment as originating based on the location of the first investor as given on Crunchbase. It was necessary to de-duplicate the Crunchbase investments versus the investments reported on 3DprintingIndustry.com. We found that 105 investments appeared in both data sources and these duplicates were dropped. A total of 310 observations were obtained from Crunchbase.com.

Some reported investments from Crunchbase were quite small, the smallest being near $1000. We speculate that it is unlikely that small investments are made by professional investment firms and that very small investments could arise from either very early-stage businesses or non-/semi-professional investors or crowdfunding financing. Since we have no reason to believe that very small investments have the same dynamics as multi-million dollar ones, we have screened out these observations. We have kept what are more unambiguously likely to be professionally made investments at the amount of $100,000 or greater. We leave the topic of the dynamics of small/layperson investments for 3D printing as one for future research. After excluding small investments and observations with incomplete data the final sample size of our early-stage firms in the 3D printing industry ecosystem was 500.

3.1.2 Labor Costs/Wages

We used the Prices and Earnings wage data from Union Bank of Scotland (UBS) (2018) for our two wage variables (source country wage and destination country wage). This data set uses a basket of 15 professions and a variety of worker ages, family statuses, and educations to generate the metrics. Earnings in local currencies are converted to US dollars and then indexed to a baseline (New York) for comparability. The data set has extensive coverage of countries which was valuable to limit the introduction of missing values. Additionally, for many countries there are separate local values for certain major cities. This characteristic allowed us to incorporate intra-national wage data, when available, for a higher level of localized specificity in wages. For Germany, city-specific data was used when the investor or the recipient was identified as being located in Berlin, Frankfurt or Munich; otherwise a national average combined by averaging these cities was used. For mainland China, city-specific data was used when the investor or the recipient was identified as being located in Beijing or Shanghai, otherwise a national average combined by averaging these cities was used. Separate values for Hong Kong and Taiwan were used for these locations. For Canada, city-specific data was used when the investor or the recipient was identified as being located in Montreal or Toronto; otherwise a national average combined by averaging these cities was used. For the USA, the value for Chicago was used for locations in the Midwest. The value for New York was used for locations in New England through the Mid-Atlantic. The value for Miami was used for locations in Florida. The value for Los Angeles was used for locations on the West Coast. For other US locations, an average of the above US city values was used. For other locations, the value from the particular nation's city was used regardless of the actual city in which the investment occurred. Wages were recorded for both the source location of the investment as well as the destination location of the investment. 2012 data was used for investments between 2011 and 2013, 2015 data was used for investments between 2014 and 2016, and 2018 data was used for investments in 2017 and 2018. Due to an absence of data for Singapore, the corresponding value for Hong Kong was substituted for the three instances of Singapore in the final data set.

3.1.3 Innovation

We used the Innovation Output sub-index values from the Global Innovation Index (Cornell University, INSEAD, and WIPO, 2018) for our two country-level innovation variables. The overall Global Innovation Index is derived from 80 country-level indicators for 126 worldwide economies that are captured annually. The innovation output sub-index is composed of creative outputs and knowledge and technology outputs. These include measures such as patent applications, high-tech exports, and creative goods and services production. Data is available for the years 2013 through 2020. The 2013 value was used for investments that occurred in 2012.

3.1.4 Human Capital

We used the World Bank's (2020) Human Capital Index. This country-level index ranges from 0 to 1 with larger values indicating higher human capital. This dataset has been collected for the years

2010, 2017, 2018 and 2020. We used the 2010 data for observations in our dataset that occurred during or before the year 2013. We used the 2017 data for observations in our dataset that occurred from the beginning of 2014 to the end of 2017. We used the 2018 data for observations in our dataset that occurred in the year 2018. Finally, we used the 2020 data for observations in our dataset that occurred from the beginning of 2019 to the end of 2020.

3.1.5 Domestic versus International Investment

If the dyad of the investing firm and the recipient firm are located in the same country, then the investment is considered as domestic. If the dyad of the investing firm and the recipient firm are not located in the same country, then the investment is considered as international. Therefore, we created a variable called International to examine different relationships that transpire from domestic investment versus international investment. This variable takes the value of zero if the source of the investment and the recipient of the investment were in the same country and the value of one if the source of the investment and the recipient of the investment were not in the same country.

3.1.6 Institutional Environment

We also controlled for differences in the institutional environments of both the investment source and the investment destination by including these as covariates in selected models. The attractiveness of an investment destination can depend on the presence of business-friendly institutional frameworks (Moore et al., 2015; Cumming and Zhang, 2019; Swoboda and Sinning, 2022). We used the Institutions sub-index from the Global Innovation Index (Cornell University, INSEAD, and WIPO, 2018) for our two country-level variables. This sub-index assesses the political, regulatory and business environments existing in a given country in a given year. Components of this sub-index include measures regarding the rule of law, political stability and the ease of starting a business. Data is available for the years 2013 through 2020. The corresponding 2013 value was used for investments that occurred in 2012.

3.2 Methods

We used random-effects regression models for unbalanced panel data to examine our hypotheses. The size of the financial investments in our dataset varied widely and exceeded three orders of magnitude, causing extreme right-skewness in the data. We applied the log transformation (Lancaster, 2004, p. 258) and computed D'Agostino et al.'s (1990) test to examine the success of this transformation. The null hypothesis of normal skewness on the untransformed data was clearly rejected ($\chi^2(2) = 560.69$, $p < 0.0001$), confirming a departure from the null hypothesis of normality. After applying the log transformation, we could no longer reject this null hypothesis ($\chi^2(2) = 0.89$, $p = 0.6412$). A Box-Cox (1964) plot of the profile log-likelihood using regression residuals also supported the use of the log-transformed dependent variable versus the untransformed dependent variable. The log transformation of the dependent variable gives the regression coefficients the semi-log interpretation familiar from econometrics (Wooldridge, 2000, p. 184). The coefficients indicate the approximate expected percentage change in the dependent variable associated with a one-unit change in the independent variable.

Given that some 3D printing companies in our data received multiple investments over the 2012-2020 time period, a panel data method is appropriate. We used random intercepts hierarchical models for estimation. All models took the form of

$$\log(\text{AmountInvested}_{ij}) = \alpha + \beta_1 x_{1ij} + \ldots + \beta_k x_{kij} + \nu_i + \varepsilon_{ij} \qquad (1)$$

where *I* indexed the individual companies and *j* indexed the observations regarding company *i*. The individual random intercepts and error terms ε_{ij} are not of theoretical interest and are not reported; however we report their standard deviations σ_ν and σ_ε.

Another consideration for our data is that the measurement level of the data varies and there may be endogeneity across levels. Recall the decision process of the investors. Investors are making a firm-level investment (here, our dependent variable). We suppose that investors find 3D printing attractive for wage cost reduction per H1, and that investors will also consider country-level human capital, innovation, and institutional environment factors. However, wages are likely affected by country-level human capital, innovation, and institutional environment factors. Hence the wage data is likely to be endogenously determined. Therefore, we used multi-equation models and created instrumental variable two-stage least squares models (2SLS) to account for these relationships (Wooldrige, 2002, ch. 8). In short, if we take x_{1ij} from (1) as endogenously determined we can relabel it as a *y* variable and write the first- and second-stage equations as follows:

$$y_{1ij} = \varphi + \xi_1 \mathrm{w}_{1ij} + \ldots + \xi_h w_{hij} + \zeta_1 z_{1ij} + \ldots + \zeta_m z_{mij} + \omega_{ij} \qquad (2)$$

$$\log(\mathrm{AmountInvested}_{ij}) = \alpha + \gamma_1 y_{1ij} + \beta_1 x_{1ij} + \ldots + \beta_k x_{kij} + \nu_i + \varepsilon_{ij} \qquad (3)$$

where *w* indexed by *h* are referred to as instruments and do not appear in (3), and *z* indexed by *m* are referred to as exogenous and may also appear in (3) as x_{ij}. In this formulation y_{1ij} is allowed to be correlated with ε_{ij} while ω_{ij} and exogenous $\boldsymbol{x}_{ij}$ are assumed to be uncorrelated with ε_{ij}. The model replaces the observed value of y_{1ij} in the second stage (3) with the fitted value of y_{1ij} found from its first-stage estimation in (2), giving the 2SLS model.

The international investment dummy variable is also at the country level. Given the large labor markets examined here, there is little reason to believe that any particular small-scale early-stage investment would have appreciable impact on regional/national wages.

3.3 Results

Table 1a contains a list of our variables and their sources, while Table 1b contains summary statistics for the variables in the study. The International variable shows that about 23% of the investments crossed a national border while the remaining were domestic investments. There were 38 source countries from which investment originated in our data. Table 2 contains descriptive analyses of the top-five most frequent sources of capital for investments in 3D printing, and the percentage of investments made from that country that were international. Germany and Japan had the highest percentages of investments going to international recipients. UK investors had a more moderate tendency to undertake international investment in 3D printing, followed by the US. At the other end of the spectrum, China's investments in 3D printing were mostly domestic with less than 5% going abroad. France was the sixth largest originator of 3D printing investments but on a percentage basis fewer of these were outside of France (15.3%). The remaining countries are pooled and reported in both tables as a single category, "All Others", as individually they only have single digits total investments, both as source and as destination.

In Table 3 we report similar descriptive analyses for the 34 recipient countries of investment. Here Germany stood out as receiving a top-five quantity of investments into 3D printing firms where a large proportion of investments (40.9%) were international. Per Tables 2 and 3, Germany was a global crossroads for 3D printing investments during the study time period. Israel had an even higher percentage (52.9%), so it could be considered a destination for international investment in early-stage

3D printing ecosystem firms. The United Kingdom was also an attractive destination for international investment in early-stage 3D printing ecosystem firms. With its moderate position in the list, the UK occupies a second place position as a global crossroads for 3D printing investment considering Table 2. Like Israel, Canada attracted the bulk (75%) of its investments from abroad (see Davidson, 1980, for similar findings regarding Canada's above-average international investment). China and the US attracted lower proportions of international investment into 3D printing firms. Finally, French 3D printing firms attracted no international investors (0%) and were exclusively domestic investment targets in our sample. These tables provide a signpost for the relevance of international business dynamics among innovative early-stage firms in the 3D printing industry.

Table 1a – List of Variables and their Sources

Name variables	Sources
Investment log(AmountInvested)	3DPrintingIndustry.com and Crunchbase.com, for investments larger than $100,000 in the 3D printing technology, 2013-2020. The data have been transformed to their logarithmic values.
International	Dummy variable if the destination country is different from the country source of the investment: "1" if the investment is international, "0" if domestic.
Wage SourceWage RecipWage	Prices and Earnings wage data from Union Bank of Scotland (UBS) (2018). When available, we used regional or city specific data, e.g., Berlin, Frankfurt, Munich for Germany; Beijing and Shanghai for China; Montreal and Toronto in Canada; New York, Chicago, Miami and Los Angeles were used for specific States or regions. Local wages in local currencies are converted to US dollars and then indexed to a New York as a baseline (New York = 100).
Innovation SourceInnovation RecipInnovation	Innovation Output sub-index values from the Global Innovation Index (Cornell University, INSEAD, and WIPO, 2018). The innovation output sub-index is composed of creative outputs and knowledge and technology outputs. These include measures such as patent applications, high-tech exports, and creative goods and services production. Data is available for the years 2013 through 2020. The 2013 value was used for investments that occurred in 2012.
Human Capital SourceHumanCapital RecipHumanCapital	World Bank's (2020) Human Capital Index. This country-level index ranges from 0 to 1 with larger values indicating higher human capital. This dataset has been collected for the years 2010, 2017, 2018 and 2020. We used the 2010 data for observations in our dataset that occurred during or before the year 2013. We used the 2017 data for observations in our dataset that occurred from the beginning of 2014 to the end of 2017. We used the 2018 data for observations in our dataset that occurred in the year 2018. Finally, we used the 2020 data for observations in our dataset that occurred from the beginning of 2019 to the end of 2020.
Institutions SourceInstitutions RecipInstitutions	Institutions sub-index from the Global Innovation Index (Cornell University, INSEAD, and WIPO, 2018) for our two country-level variables. This sub-index assesses the political, regulatory and business environments existing in a given country in a given year. Components of this sub-index include measures regarding the rule of law, political stability and the ease of starting a business. Data is available for the years 2013 through 2020. The corresponding 2013 value was used for investments that occurred in 2012.

Table 1b – Variable Descriptive Statistics and Pearson Correlations

		Mean	*s.d.*	1	2	3	4	5	6	7	8	9
1	log(AmountInvested)	*14.90*	*1.77*	—								
2	International	*0.23*	*0.42*	0.103	—							
3	SourceWage	*88.09*	*31.13*	0.210	0.068	—						
4	SourceInnovation	*50.12*	*6.57*	0.152	0.011	0.503	—					
5	SourceHumanCapital	*54.26*	*6.57*	0.151	0.104	0.564	0.646	—				
6	RecipWage	*85.39*	*30.32*	0.262	-0.009	0.809	0.360	0.479	—			
7	RecipInnovation	*49.78*	*6.74*	0.203	-0.082	0.382	0.690	0.504	0.513	—		
8	RecipHumanCapital	*53.90*	*6.77*	0.195	0.003	0.492	0.483	0.726	0.610	0.681	—	
9	SourceInstitutions	*81.43*	*12.14*	0.190	0.150	0.812	0.453	0.670	0.717	0.344	0.562	—
10	RecipInstitutions	*81.16*	*12.32*	0.231	0.113	0.701	0.341	0.583	0.809	0.432	0.675	0.856

N = 500.

Table 2 – Top 3D Printing Capital Investment Source Countries – Total, Domestic and international Destinations

	Total		Domestic		International	
US	224	44.8%	184	82.1%	40	17.9%
China	62	12.4%	59	95.2%	3	4.8%
UK	58	11.6%	40	69.0%	18	31.0%
Germany	24	4.8%	13	54.2%	11	45.8%
Japan	14	2.8%	8	57.1%	6	42.9%
France	13	2.6%	11	84.6%	2	15.4%
Sweden	10	2.0%	7	70.0%	3	30.0%
All Others (31)	95	19.0%	63	66.3%	32	33.7%
Total	500	100.0%	385	77.0%	115	23.0%

Table 3 – Top 3D Printing Capital Investment Recipient Countries – Total and From Domestic and International Sources

	Total		Domestic		International	
US	213	42.6%	184	86.4%	29	13.6%
China	63	12.6%	59	93.7%	4	6.3%
UK	53	10.6%	40	75.5%	13	24.5%
Germany	22	4.4%	13	59.1%	9	40.9%
Israel	17	3.4%	8	47.1%	9	52.9%
Canada	16	3.2%	4	25.0%	12	75.0%
France	11	2.2%	11	100.0%	0	0.0%
All Others (27)	105	21.0%	66	62.9%	39	37.1%
Total	500	100.0%	385	77.0%	115	23.0%

Next, we estimated inferential models. Table 4 contains our results when the concept of endogeneity is temporarily ignored. It is conventional to check the adequacy of the random effects specification against the fixed effects specification. We use Model 3 for this test as it is the most comprehensive model in terms of variables. A Hausman test for Model 3 ($\chi^2(9) = 7.83$, $p = 0.5518$) indicates we cannot reject the more efficient random effects specification. We also calculated variance inflation factors (VIFs) as a check. Different authors disagree regarding cut-off values for VIFs. Stine (1995) suggests that VIFs between 5 and 10 are increasingly problematic, especially at the end of this range and above. Chatterjee and Hadi (2012) give a cut-off of 10 for VIFs. In a worst-case scenario with all predictors entered, our VIFs satisfy the Chatterjee and Hadi (2012) cut-off (all VIFs < 7.4). We expect that endogeneity partly accounts for the larger VIFs (and treat this issue below). For example, our purely exogenous variable, International, had a VIF of 1.07 and it is reasonable to expect that accounting for endogeneity would improve estimation.

For Model 1, we entered our four hypothesis-generating variables (RecipWage, RecipInnovation, RecipHumanCapital and International) with respect to recipient countries of investment. We find Hypothesis 1 regarding the effect of wage costs in recipient countries was supported ($\beta = 0.0084$, p =

0.019). More specifically, larger financial investments into early-stage 3D printing ecosystem firms were made into recipient (destination) countries with higher wages, and smaller investments were made into recipient countries with lower wages. We also find that the International dummy variable was positive and significant ($\beta = 0.472$, $p = 0.005$), corresponding to Hypothesis 4B. We can observe that under the semilog interpretation of the model coefficients, the International dummy variable with $\beta = 0.472$ can be unpacked to mean the following: internationally originated early-stage investments into 3D printing firms are approximately 47.2% larger than domestically originated early-stage investments *ceteris paribus*. More broadly, multiplying any predictor variable's coefficient by 100 gives the approximate percent change in the amount invested that is associated with a one-unit change in the predictor variable. The practical effect of the international variable being 1 or 0 is that the investor and the recipient are not located in the same country when the variable is 1, and the investor and the recipient are located in the same country when the variable is 0. At the bottom of the Model 1 column we provide model fit chi-squared statistics and AIC. For Model 2, we entered RecipWage, RecipInnovation, and RecipHumanCapital) and their source country counterparts (SourceWage, SourceInnovation, and SourceHumanCapital), plus International. Hypothesis 1 ($\beta = 0.0084$, $p = 0.019$) and 4B ($\beta = 0.5014$, $p = 0.006$) was again supported. Again, we can unpack the coefficient for International to find that internationally originated early-stage investments into 3D printing firms are approximately 50.1% larger than domestically originated early-stage investments *ceteris paribus*. For Model 3, we entered our four hypothesis-generating variables (RecipWage, RecipInnovation, RecipHumanCapital, and International) as well as all other variables appearing in Table 1 as control variables. In Model 3 we see again that Hypothesis 1 regarding recipient wages was supported ($\beta = 0.0117$, $p = 0.05$) and that Hypothesis 4B regarding international investment was supported ($\beta = 0.4844$,

$p = 0.005$). As a method of model comparison, we included Akaike's Information Criterion (AIC) for Models 1 through 3. Here Model 1 is regarded as the most parsimonious model by AIC.

We then examined possible relationships of endogeneity and have included these findings in Table 5. At top left of the table, we indicate that the Stage 1 instrument is SourceWage. We then list the exogenous variables and instruments for SourceWage that were included in a particular model, and provide their coefficient estimates and test statistics. Next at middle left of the table we indicate the Stage 1 instrument is RecipWage. We then list the exogenous variables and instruments for RecipWage that were included in a particular model and provide their coefficient estimates and test statistics. About two-thirds of the way down at left in the table we indicate that the Stage 2 coefficient estimates and test statistics are listed next. 2SLS makes use of computationally attractive least-squares estimation; however AIC cannot be naturally calculated since a likelihood function has not been numerically maximized. Therefore AIC values are unavailable for the models of Table 5.

Table 4 – Random Effects Regression Results

	Model 1				Model 2				Model 3			
	Coef.	s.e.	t	p	Coef.	s.e.	t	p	Coef.	s.e.	t	p
(Intercept)	12.554	0.726	17.3	—	12.644	0.790	16.01	—	12.213	0.906	13.48	—
International	0.4720	0.169	2.79	**0.005**	0.5014	0.17	2.95	**0.003**	0.4844	0.171	2.83	**0.005**
SourceWage					-0.0068	0.005	-1.51	0.132	-0.0081	0.005	-1.55	0.121
SourceInnovation					0.0104	0.019	0.56	0.578	0.01043	0.019	0.56	0.578
SourceHumanCapital					-0.0080	0.02	-0.41	0.685	-0.0123	0.021	-0.59	0.553
RecipWage	0.0084	0.004	2.35	**0.019**	0.0140	0.005	2.75	**0.006**	0.0117	0.006	1.96	**0.050**
RecipInnovation	0.0150	0.016	0.94	0.346	0.0072	0.02	0.37	0.713	0.00944	0.020	0.47	0.635
RecipHumanCapital	0.0109	0.016	0.66	0.508	0.0167	0.021	0.82	0.415	0.01364	0.022	0.63	0.526
SourceInstitutions									0.00601	0.016	0.38	0.707
RecipInstitutions									0.00677	0.016	0.43	0.668
σ_v	1.237				1.241				1.245			
σ_ε	1.111				1.103				1.099			
AIC	1861.3				1864.4				1867.5			
Model χ^2	$\chi^2(4)=25.94, p < 0.0001$				$\chi^2(7)=28.79, p = 0.0002$				$\chi^2(9)=29.74, p = 0.0005$			

$N = 500$.

In Model 4A we estimate a simpler 2SLS model examining the idea that SourceWage is instrumented by country-level innovation output and country-level human capital. We find strong evidence of these predictive relationships in Model 4A. SourceInnovation ($\beta = 1.368$, $p < 0.0001$) and SourceHumanCapital ($\beta = 1.453$, $p < 0.0001$) strongly predict SourceWage. Failure to reject the null with the Sargen-Hansen p value (which occurred for this and subsequent models, see Table 5) provides evidence that the model's instruments satisfy the exogeneity criterion and are valid. Instrument relevance is a key issue for 2SLS. We therefore calculated the Cragg-Donald F statistic to examine the possible issue of weak instruments but found it well-exceeded even the most conservative critical value tabulated by Stock and Yogo (2005), indicating that poor estimator performance due to weak instruments was not supported. We estimated Model 4A for completeness since the second stage of Model 4A does not speak to our hypotheses, but the first stage supports the concept of our instrumental variables. In Model 4B we repeat the simpler model focusing on RecipWage. RecipInnovation ($\beta = 1.026$, $p < 0.0001$) strongly predicts RecipWage and RecipHumanCapital ($\beta = 1.717$, $p < 0.0001$) strongly predicts RecipWage. The Cragg-Donald F statistic again rejected the notion of weak instruments (this also occurred for Model 5 and 6, to be reported, so we do not comment on this further). The second stage of Model 4B shows that SourceWage has a strong positive relationship with investment ($\beta = 0.0172$, $p < 0.0001$), supporting Hypothesis 1. Taken with the first-stage findings of Model 4B, we have some indirect information pertaining to Hypothesis 2 and Hypothesis 3. Namely country-level innovation output (H2) and country-level human capital (H3) predict wages, which then predicts investment. These relationships appear to be indirect since they did not appear in Models 2 or 3.

In Model 5 we include two instruments (SourceWage and RecipWage), and include the exogenous International variable. The second stage results support Hypothesis 1 ($\beta = 0.021$, $p = 0.005$)

and Hypothesis 4B (β = 0.454, $p = 0.009$). The first stage again displays the suggestive pattern of indirect Hypothesis 2 and 3 relationships. We see that SourceInnovation (β = 1.134, $p < 0.0001$) and RecipInnovation (β = 1.425, $p < 0.0001$) are again significant. The first-stage results for SourceWage also display significant relationships, but again these are peripheral to our hypotheses. The two model fit chi-squares at Stage 1 were very large so we list the smaller of the two and indicate this with the ≥ sign. Model 6 examines the effect of country-level institutional environment. We find that at the second stage Model 6 supports Hypothesis 1 (β = 0.019, $p = 0.002$) and Hypothesis 4B (β = 0.462, $p = 0.006$). At the first stage for RecipWage, we again find suggestive information regarding Hypothesis 2. RecipInnovation (β = 1.042, $p < 0.0001$) significantly predicts RecipWage. We also find that adding SourceInstitutions (β = 0.510, $p < 0.0001$) and RecipInstitutions (β = 1.231, $p < 0.0001$) reveals strong relationships with RecipWage. However, the previous relationship for RecipHumanCapital (β = 0.249, $p = 0.204$) disappears with this addition.

Table 5 – 2SLS Regression Results

		Model 4a				Model 4b				Model 5				Model 6			
		Coef.	*s.e.*	*t*	*p*	*Coef.*	*s.e.*	*t*	*p*	*Coef.*	*s.e.*	*t*	*p*	*Coef.*	*s.e.*	*t*	*p*
	Stage 1 (SourceWage)																
Stage 1	(Intercept)	-61.896	9.796	-6.32	—	-58.962	8.256	-7.14	—	-71.858	10.78	-6.67	—	-97.914	8.135	-12.0	—
(SourceWage)	International									3.999	2.395	1.67	0.095	1.169	1.789	0.65	0.514
	SourceInnovation	1.399	0.203	6.88	**<.0001**					1.593	0.240	6.64	**<.0001**	0.958	0.186	5.14	**<.0001**
	SourceHumanCapital	1.461	0.212	6.89	**<.0001**					0.858	0.277	3.10	**0.002**	-0.446	0.217	-2.05	**0.040**
	RecipInnovation									-0.331	0.262	-1.26	0.207	-0.045	0.198	-0.23	0.818
	RecipHumanCapital									0.897	0.282	3.18	**0.001**	0.281	0.226	1.24	0.214
	SourceInstitutions													1.867	0.144	13.00	**<.0001**
	RecipInstitutions													-0.043	0.146	-0.29	0.771
	Stage 1 (RecipWage)																
Stage 1	(Intercept)									-63.704	9.449	-6.74	—	-90.513	7.036	-12.9	—
(RecipWage)	International									2.261	2.100	1.08	0.281	-1.4462	1.548	-0.93	0.350
	SourceInnovation									-0.162	0.210	-0.77	0.441	-0.266	0.161	-1.65	0.099
	SourceHumanCapital									0.418	0.243	1.72	0.085	-0.323	0.188	-1.72	0.086
	RecipInnovation					1.026	0.189	5.42	**<.0001**	1.134	0.230	4.94	**<.0001**	1.042	0.171	6.08	**<.0001**
	RecipHumanCapital					1.717	0.206	8.34	**<.0001**	1.425	0.247	5.76	**<.0001**	0.249	0.196	1.27	0.204
	SourceInstitutions													0.510	0.124	4.10	**<.0001**
	RecipInstitutions													1.231	0.127	9.72	**<.0001**
	Stage 2 log(AmountInvested)																
Stage 2	(Intercept)	13.910	0.414	33.61	—	13.256	0.396	33.47	—	13.245	0.432	30.64	—	13.453	0.321	41.95	—
	International									0.454	0.171	2.65	**0.009**	0.462	0.170	2.73	**0.006**
	SourceWage	0.0091	0.005	1.96	**0.05**					-0.005	0.007	-0.70	0.484	-0.006	0.006	-1.03	0.303
	RecipWage					0.0172	0.005	3.53	**<.0001**	0.021	0.008	2.78	**0.005**	0.019	0.006	3.13	**0.002**
	Sargan-Hansen *p*	0.579				0.909				1.321				1.321			
	σ_v	1.463				1.317				1.103				1.103			
	σ_ε	1.164				1.111				1.099				1.099			
	N = 500.	Stage 1 χ^2(2)=238, *p* <0.0001				Stage 1 χ^2(2)=323, *p* <0.0001				Stage 1 χ^2(2)>=256, *p* <0.0001				Stage 1 χ^2(7)>=871, *p* <0.0001			
		Stage 2 χ^2(1)=3.84, *p* = 0.0501				Stage 2 χ^2(1)=12.48, *p* =0.0004				Stage 2 χ^2(3)=20.49, *p* =0.0001				Stage 2 χ^2(3)=24.65, *p* < 0.0001			

4. Discussion and conclusions

The current paper studies the geography of eco-systems in the context of a specific technology (3D printing) and its development, from the proxy of investment. By doing this, it extends the literatures on the areas of international entrepreneurship, international SME financing, and the emerging area of 3D printing. Scholars have suggested that the Industry 4.0 technologies are likely to reconfigure location advantages and the geography of production and global value chains (Strange and Zucchella, 2017; Hannibal and Knight, 2018; Strange et al., 2022). At the same time, scholars have focused on the relation between Industry 4.0 and manufacturing location decisions, backshoring and reshoring (Foerstl et al., 2016; Ancarani et al., 2019; Dachs et al., 2019). 3D printing technology is instrumental to some dynamics related to location and relocation of manufacturing activities. Due to its ability of reducing the time for developing new products and prototypes, as well as supporting small scale production, 3D printing is often utilized by companies located in high cost, developed countries. However, this is still a developing technology which is experiencing substantial innovative activities and investments in all parts of the ecosystem. In order to better understand the trends on its impact on the reconfiguration of production, innovation processes of adopting businesses, and the geographical reconfiguration of processes using 3D printing, it is important to understand patterns of innovation and investments in these technologies. Goldberg et al. (2022) observed that shareholder wealth impacts of 3D printing have received scant empirical inquiry to date, and they examined relatively large market capitalization firms (their median firm market capitalization was $8 billion USD). Their research methodology provides a valuable contrast to ours as it was an event study of cumulative abnormal returns in publicly-traded investment source firms. Some of their sample firms (including Johnson & Johnson and Unilever) may have been the *sources* of some of the investments we examine here, although our methodologies, variables and data sources differ. Our research complements theirs by examining the factors that affect the amounts invested into (much smaller pre-public offering) *recipient* 3D printing firms to provide a unique view of a phenomenon that would be otherwise difficult to observe. There are very few large multinational corporations that specialize in 3D printing technology (Stratasys being the largest), and internal financial investments that are private cannot be modeled. Furthermore, the dynamics of a multinational's internal investment are almost certainly different from the dynamics of an outside venture capital firm's investment into a smaller start-up business.

3D printing has a unique value proposition portfolio; however, it remains an open empirical question as to which aspects of the value proposition most motivate investors to part with their capital. Our results find support for Hypothesis 1 and the role of labor cost in 3D printing development and investments. Labor costs at the destination of the investment have a significant positive relationship with the amount of capital invested. We argue that this is in part because of the role of 3D printing in displacing and disrupting conventional production processes which rely on higher skilled labor, and that 3D printing may eventually disrupt lower skilled labor as value chains are reconfigured.

Our models also support Hypothesis 4b, that investors tend to invest larger sums when they invest in 3D printing ventures in foreign countries, over Hypothesis 4a, which argues that investors tend to invest larger sums in 3D printing ventures domestically. It would appear that the investors with the greatest sums of money look globally for attractive and potentially more challenging, riskier, but also potentially more lucrative deals. Conversely, smaller 3D printing investment opportunities may tend to attract more domestic involvement. This may be due to the investment being achievable with smaller pockets. Also, domestic investors may be more familiar with local, smaller scale innovative endeavors by smaller companies less known in the global business and technological arenas. Or perhaps a domestic investor has the inside knowledge to provide tolerance for riskier, earlier-stage investments that are still small due to their more nascent state. Our Models 1 through 3 indicate that aspects of the source country were not influential here, suggesting that it is the characteristics of the countries where the development of the technology that may create an environment favorable to the success of innovation and that is what matters to investors. Financial capital is mobile and is directed towards locations that can bring returns. In their first estimation, Models 1 through 3 provided no support for Hypotheses 2 and 3, respectively about the level of innovation infrastructure and the presence of advanced human capital in the recipient country. However, once we addressed the issue of endogeneity we have found some patterns that suggest a more nuanced dynamic of those variables, with the innovation level and the human capital of the recipient and source countries positively affecting the wage levels of source and recipient countries, and, in turn, the wage of the recipient country having a positive relationship with the size of the investments. From the point of view of the investors, who are more interested in the returns to their investments, the main drivers are the innovation levels of both recipient and source countries, as well as the degree of development of institutions in both recipient and source countries.

Interestingly, human capital in the recipient company has a positive effect on the wage of the recipient country, until we include the role of institutions in both, at which point the effect disappears. This could be due to the fact that aspects related to the political, regulatory and business environment such as rule of law, political stability and the ease of starting a business are more relevant to investors than the presence of human capital. This is consistent with the fact that investors are particularly concerned about the security of their investments, which should be based in an institutionally stable environment which minimizes the disruption due to external factors, such as volatility of the financial and political environment. Thus, foreign investors may be more willing to take more risk if the investment is in locations with strong institutional infrastructure.

From the point of view of companies developing 3D printing technology, our research offers multiple contributions. First, if managers are seeking investments, being located in a country with a strong innovative environment and human capital availability makes it more likely to attract larger investments. From the point of view of the investors, locations with stronger institutional infrastructure are more attractive than environments with higher human capital endowment. This is an encouraging message for developers of 3D printer technologies located in countries such as Canada which may not enjoy high levels of domestic financial investors but can attract foreign capital. Additionally, managers are interested in generating profit through enterprise. The investment trends described in this paper are consistent with the anyshoring perspective outlined above which implies that the high cost locations may be particularly attractive for managers to build (or invest in) capacity in 3D printing. Though our paper does not cover reshoring per se, the management implications of reshoring have parallels in our work – namely, the dynamic changes in the global environment due to innovation and technological development cause new opportunities for advancements in enterprise in locations that previously seemed less attractive. Finally, our paper gives managers of early-stage 3D printing companies a powerful incentive to look abroad for investment partners. Our Models 1, 2, 3, 5, and 6 show that investors from abroad invest 40% to 50% more than do domestic investors *ceteris paribus*. While we cannot guarantee that this will be true for all early-stage 3D printing firms, the prospect of attracting considerably larger investments would be of interest to most managers.

Public-policy implications of the paper lead to the consideration of a host government's ability to foster or (inadvertently) deter international investments in their nation's 3D printing industry. Policy makers can utilize our contribution that our paper shows the importance of fostering institutional infrastructure that benefits investors and investment recipients. The current work suggests that labor cost destruction is a powerful investment determinant, and this factor may be largely outside of government control without draconian intervention. Policy makers should also reflect on our finding that political, regulatory and business environment factors such as the rule of law, political stability and the ease of starting a business are more relevant to investors than the presence of human capital. Policy makers may therefore wish to facilitate the development of institutions that make investment attractive, as previously mentioned. As this paper is the first (to our knowledge) empirical investigation of international and domestic early-stage investment into 3D printing SMEs, opportunities for future research arise. Managerial decision making about the location of innovative activities within the early stage 3D printing ecosystem and investments in such activities is an example of a future avenue for research, particularly given the more macro level of the current analyses. The actual managerial process of deciding or not deciding to invest in a particular firm, as well as other firm-level decisions about where to (any)shore their production, or how much capacity to add, will be important questions for future research. This paper contributes to recent calls for research into the many theoretical and research gaps on international business ecosystems and global strategy (Cha, 2020; Rong et al., 2022, Strange et al., 2022). For example, this paper contributes to Cha's (2020) call for research on the strategic dimensions that determine the relative competitive positioning of entities within a business ecosystem and to Cha's call for research on the institutional dimensions that affect the dynamics of investment into business ecosystems. This paper also contributes synergistically to recent work by Goldberg et al. (2022) in which stock market announcements regarding 3D printing were examined. Goldberg et al. (2022) examined publicly traded firms which by definition have left the start-up phase. Here we examine an earlier stage in the business lifecycle than Goldberg et al. (2022). This paper also contributes to the empirical testing of theory-derived propositions in the area of early-stage investments into firms in the 3D printing industry.

Limitations of the current study include the fact that only investments documented at 3DPrintingIndustry.com and Crunchbase.com were included. While industry websites have the motivation to cover as much relevant information as possible to increase traffic and thus advertising revenue (3DprintingIndustry.com) or paid subscriptions (Crunchbase.com), no news source (3DprintingIndustry.com) or database aggregator (Crunchbase) can cover every activity in a given industry. It is reasonable to suppose that the smaller the investment, the less newsworthy it may have been perceived, and hence the less likely it would have been reported on at 3DprintingIndustry.com. This was less evident at Crunchbase which captured some very small investments. To focus the current research on professionally-made investments and to make the two data sources more comparable, we only retained observations where the investment was $100,000 or greater. With that in mind, the conclusions of the current research may apply only to larger investments into early-stage firms in the 3D printing ecosystem. Smaller investments into 3D printing firms (below $100,000) may be subject to a different set of considerations, a topic we leave for future research. We have also examined the existence of endogeneity and alleviated this threat through 2SLS. However, a larger panel data set would be useful for more detailed examination of the current hypotheses as well as of the suggestive relationships uncovered by the current research. It is possible that our data sources have some selection bias which we have not discussed above and which they have not disclosed to their customers. Also, as a part of the review process, we assembled a very large dataset of 3D printing patent activity similar to that of De Beule et al. (2022) for a parallel analysis and we used this to investigate whether our country-based representation was consistent with 3D printing patenting information. We found highly significant Spearman rank coefficients of 0.54 or greater in several parallel analyses, lending at least some external validity to the scope of our data given that investment and patenting are not identical activities. Therefore, our generalizability is limited by the characteristics of industry/business news/media and the availability of publicly reported investment information. Nevertheless, whilst acknowledging that no researcher has a universal dataset consisting of the entire population of 3D printing businesses, our data source does appear to be one of the more comprehensive to date and we appear to be one of the first to have performed an external validation of our data against an entirely different but related set of industry information, that of patents. Further limitations include the fact that there is no universal data source for these emerging-level investments into 3D printing firms, a limitation that may apply to other papers in this area. We cannot claim that our results hold for all of the almost 200 nations in the world, and it is possible that our results may not apply to investments in Africa for which there were no observations in our data set. Ideally an organization such as the United Nations would have a comprehensive worldwide data set but to the best of our knowledge such a data set does not exist for early-stage 3D printing investments. We also recognize that some investments into early-stage firms (including those in the 3D ecosystem) do not have public announcements or else the financial details are suppressed.

We of course cannot generalize our results to these kinds of investments and so this may also be regarded as a limitation of the research. This can also be considered a scope issue – for example, Goldberg et al. (2022) looked at the effects of 3D printing announcements on publicly-traded firms, implying that privately-held firms were out of scope for their research.

As the area of 3D printing research starts to become more mature, it is a worthwhile contribution to move toward the specification and testing of theory-derived propositions. Specification and testing of theory-derived propositions help the academic community advance the boundary of knowledge in a different and complementary direction to that of case-study and descriptive research. We believe that with time the extent of innovation, investments, development and adoption of 3D printing will increase, and more nuanced studies will build on our insights. Future research could examine the role of the innovation environment and human capital (our Hypotheses 2 and 3) in more detail. Future research could also explore the topic of possible microfinance or layperson investment in 3D printing firms. The current research is limited to the dynamics of larger capital investments likely made by angel capitalists/professional venture capital firms, but future research could consider the embryonic phase of investment into 3D printing by looking at the dynamics of very small investments.

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