Internationalization, Value-chain Configuration, and the Adoption of Additive Manufacturing Technologies

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ABSTRACT

In this study, we empirically explore the relationships among process innovation, internationalization, and the reconfiguration of the firm's activities at the global level. In particular, we analyze the extent to which these factors are related to the propensity to adopt additive manufacturing technologies. Internationalization and value-chain configuration are measured using various dimensions, and we find that the impact on the adoption of additive manufacturing technologies is moderated by firms' absorptive capacity. Our empirical findings are drawn from a proprietary database covering 197 manufacturing firms.

Keywords: global value chain; additive manufacturing; technology adoption; innovation.

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1. INTRODUCTION

In 2008, the aerospace company Boeing launched a massive outsourcing and offshoring plan at the global level to cut costs. Years later, the company admitted that this fragmentation of the value chain had failed. Jim Albaugh, Chief of Commercial Airplanes, declared: 'We spent a lot more money in trying to recover than we ever would have spent if we'd tried to keep the key technologies closer to home' (Denning, 2013, p. 6). Thereafter, Boeing reconsidered the structure of its global value chain and adopted 'smart' technologies as a strategic pillar. It renewed and digitalized its engineering platform and moved to a data-driven approach to production design, with several of these activities consolidated under a single unit. In particular, advancements in 3D printing enabled Boeing to discontinue its cooperation with several suppliers and served to reconnect research and production activities both geographically and within the organization. In 2017, Boing announced that its additive-manufactured titanium project had cut production costs by USD 3 million per airplane.[1]

The Boeing case and others like it have given rise to an intriguing debate about the possibility of going beyond the outsourcing and offshoring 'mantras' (Pisano & Shih, 2009) and, in general, reconceiving the relationship between internationalization and innovation. Is a highly fragmented and dispersed global value chain (GVC) still a competitive driver for manufacturing companies? Under which conditions is this mantra no longer valid? Do internationalization and the fine-slicing of GVCs facilitate or impede innovation? Questions like these reflect key issues among both scholars and practitioners (e.g. Buciuni, Corò, & Micelli, 2016; Dedrick, Kraemer, & Linden, 2010), and challenge several common assumptions in the innovation and international business (IB) literature.

Over the past forty years, the emergence of digital technologies, the removal of trade and investment barriers, and reductions in transportation costs have dramatically changed the

[1] See also Vincent (2017) as well as Boeing's official website and annual reports.

way organizations build up and orchestrate their manufacturing activities at the global level (Buckley & Ghauri, 2004; OECD, 2010; UNCTAD, 2013). Within these globalization and technology-related processes, firms have fine-sliced their GVCs through offshoring and outsourcing processes (Contractor et al., 2010). Studies in the IB field show that firms are locating value-chain activities in different countries in the search for better factor conditions (e.g. the presence of tech clusters for R&D or lower labor costs for production). This international fragmentation of production has led researchers to propose the idea of the 'global factory' (Buckley, 2009; Buckley & Ghauri, 2004; Buckley & Strange, 2015), which refers to changing location and internalization (governance) strategies for firms' production capacity.

The IB literature has largely examined the processes of outsourcing and offshoring manufacturing or R&D as stand-alone activities, while contributions that simultaneously investigate both dimensions – as well the interplay among them – are rare. Despite the evidence that fragmented R&D activities (Andersson et al., 2016; Cano-Kollmann et al., 2016; Mudambi, 2008) and process innovation are increasingly common in global networks (Levin & Barnard, 2013; Perri, Scalera & Mudambi, 2017; Tzabbar & Vestal, 2015), little theoretical or empirical research has provided insights into the innovation dynamics in GVCs (Pietrobelli & Rabellotti, 2011; Turkina, Van Assch & Kali, 2016). Our study helps fill these research gaps by examining the extent to which the propensity to adopt digitalized process technologies, such as additive manufacturing, is related to firms' internationalization in terms of the way they configure their GVCs and to firms' absorptive capacity in relation to new technologies. We analyze the effects of internationalization from the points of view of foreign-sales intensity and breadth of activities across multiple countries. We also investigate the effects of separating R&D and production activities on the geographical and organizational (i.e. outsourcing versus in-house) levels. Finally, we look at the role of absorptive capacity in firms' decisions about the separation of R&D and production. Knowledge about additive manufacturing (AM) is expected to make a difference over the above-mentioned technology adoption paths (Müller et al., 2021; Oettmeier & Hofmann, 2016).

Industry 4.0 constitutes a fruitful context for our research. The digital technologies applied to manufacturing, including the Internet of Things, artificial intelligence, robotics, and additive manufacturing, are driving firms towards new markets and new value-chain configurations (Despeisse et al., 2017; Maresch & Gartner, 2020; Rayna & Striukova, 2016), while reshoring practices are becoming increasingly widespread (Barbieri et al., 2018; Liao et al., 2017; Strange & Zucchella, 2018). In particular, we investigate the likelihood that companies will adopt AM technologies, which are also referred to as '3D printing'. AM refers to the 'process of joining materials to make objects from 3D model data, usually layer upon layer' (Frazier, 2014, p. 1917), in contrast to traditional manufacturing, which involves substractive processes (Janssen et al., 2014; Sasson & Johnson, 2016). AM's potential to revolutionize R&D, prototyping, and production activities is highly relevant for international business in general and GVC configuration in particular (Laplume et al., 2016; Strange & Zucchella, 2018).

Nevertheless, little research has been undertaken on the relationship between the adoption of AM technology and GVCs (Laplume et al., 2016). From a theoretical point of view, we discuss emerging conditions for GVC configuration, which lead to new regimes of complementary assets (Baumers et al., 2016; Caesarius et al., 2018). We offer both theoretical and empirical evidence on these dynamics through an explorative survey based on a proprietary database covering 197 manufacturing companies. The data, which we collected in 2016, address firms' adoption of additive manufacturing from 2013 to 2015. The time period coincides with the initial years of the fast adoption of this technology (see Figure 1). This serves as a perfect timeframe for examining firms' propensities to adopt 'emerging' technologies.

****Figure 1 about here****

The remainder of this paper is organized as follows. First, we provide a literature review and set out our theoretical framework. We then develop hypotheses regarding: a) the relationship between firms' internationalization and AM, b) the effects of geographical/organizational separation of R&D and production activities as factors influencing AM adoption, and c) the role of absorptive capacity in such dynamics. We then discuss our quantitative study's methodology as well as our descriptive statistics and analytical techniques. Lastly, we present and discuss our main findings as well as insights for future research, and acknowledge the limitations of our study.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Despite the increasing attention paid to the relationship between internationalization and innovation, findings in the field are still controversial (e.g. Cano-Kollmann et al., 2016; Denicolai, Hagen & Pisoni, 2015; Golovko & Valentini, 2011; Symeonidou, Bruneel & Autio, 2017). The mainstream view considers innovation and internationalization as alternatives, especially for small and medium-sized firms, based on the assumption that the high complexity of these activities and the significant resource requirements make it hard to simultaneously pursue both paths (Ansoff, 1957; Fatima, 2017; Kylaheiko et al., 2011). However, recent studies posit a complementarity between these two options. The key argument supporting this view is that the two processes are influenced and driven by knowledge-exploration and knowledge-exploitation processes that, in turn, benefit from exposure to diverse contexts (Gereffi & Korzeniewicz 1994; Doz et al., 2001; Schweizer 2005; Powell et al., 2005).

Within the internationalization-innovation debate, global factories – and the dispersion of their activities across the world – are of particular interest, especially in the era of smart manufacturing. Global factories have revolutionized the way in which value chains are established and activities are orchestrated (Gereffi 1989). We can envisage new, complex dynamics due to the introduction of Industry 4.0 technologies, such as AM (Strange & Zucchella, 2018).

Buckley and Strange (2015, p. 238) describe the global factory as a 'complex strategy by MNEs to reduce location and transaction costs, with global value chains linked together by international flows of intermediate products'. This view, which supports the idea that knowledge is increasingly internalized and operations are increasingly externalized (Buckley & Ghauri, 2004), has several key implications. First, global factories are critical contributors to knowledge flows across countries, either through technology spillovers mediated by foreign direct investment or through involvement in GVCs (Levin & Barnard, 2013; Perri et al., 2017; Narula & Guimón, 2010; Tzabbar & Vestal, 2015). They orchestrate finely sliced value chains that connect R&D activities in both advanced and emerging economies (Mudambi, 2008; Mudambi & Venzin, 2010; Jensen & Pedersen, 2011). Second, the fact that knowledge internalization is coupled with the externalization of operations calls for a better understanding of the systemic effects generated by outsourcing and/or offshoring. This is particularly relevant for R&D activities and production capacity, especially in terms of the implications for sliced value chains in which R&D is separated from manufacturing activities in largely modular systems.

Nonetheless, the extant literature lacks contributions addressing the effects of these dynamics on the organizational propensity to adopt new technologies, seen as an expression of a firm's overall innovation process (Liu et al., 2017; Pietrobelli & Rabellotti, 2011; Van Assche, 2016). This issue is becoming increasingly critical in both IB and innovation studies, where digital manufacturing technologies, epitomized by the Industry 4.0 concept, have prompted a discussion of GVC configuration. The emergence of digitalized manufacturing technologies is pushing firms towards a broader range of configurational options, so that the modular approach (Manello, Calabrese, Frigero, 2015) is no longer viewed as the best practice. Notably, AM relies on a different paradigm. Buckley (2009) and Oettmeier and Hofmann (2016) suggest that the AM revolution is not limited to firms' internal processes – it also has a significant impact on firms' supply chains and the way in which nodes interact with each other. In reviewing the various Industry 4.0 technologies and their impacts on GVCs' reconfigurations, Strange and Zucchella (2018, p. 7) stress that GVCs 'may be considerably simplified in terms of the number of distinct activities, their geographical dispersion, and the relationship between independent participants'.

These arguments indicate that the contemporary architectures of GVCs are inherently intertwined with the surge in AM and other digital technologies. Nevertheless, the effects of the interdependencies within the firm's value chain and the effects of technological advances on the firm's value chain are uncertain. Despite the acknowledged potential impact on firms' GVCs, this topic has largely been neglected by IB scholars, as extant studies are mainly focused on the technical aspects of AM as well as their impact on firm-specific production processes and applications in various industries (e.g. Amon et al., 1998; Bak, 2003; Gao et al., 2015; Zhai et al., 2014; see Campbell et al., 2011; Hannibal & Knight, 2018; and Laplume et al., 2016, for exceptions).

Given these considerations, we apply a revised complementary assets view within the GVC framework to advance the theoretical understanding of the conditions leading to the integration or separation of innovation activities. We propose that the digital transformation of global factories does not inevitably lead to a higher degree of fine slicing of the GVC. On the contrary, digital transformation is likely to enable alternative GVC configurations, including new forms of integration. Hence, some conventional theoretical views may need to be reconsidered. In particular, the construct of ‘integration’ may evolve from its original conception to embrace novel forms of ‘innovation integration’ that merge ‘ideation’ and ‘making’ activities.

This leads to complementary assets rooted in digitalization and the hyper-agility of modern factories. Complementary assets are those benefits that arise owing to the integration of factors in a production system that exceed the benefits generated by applying the same factors in isolation (Christmann, 2000; Kash et al., 2002; Tripsas, 1997). These kinds of assets play a critical role in the value-creation architecture (Christmann, 2000; Kash *et al.*, 2002; Tripsas, 1997). R&D and production have highly complementary assets, as their combination induces breakthrough solutions, higher quality, and cost savings (Jacobides *et al.*, 2006). However, the prevalence of modular systems in global factories has impeded the formation of these kinds of complementary assets. The emergence of digital-transformation processes, including the adoption of AM technologies, heralds a change in this scenario.

In short, we expect firms’ adoption of AM technologies to be closely related to the way in which R&D and production are orchestrated within GVCs. In particular, we argue that the fine-slicing of the GVC under certain conditions impedes the formation and leveraging of complementary assets and, thereby, the adoption of digital manufacturing technologies like AM.

3. DEVELOPMENT OF HYPOTHESES

The extant IB and innovation literature focuses on the antecedents of technology adoption at the firm level, and largely refers to factors such as firm size, absorptive capacity, complementarities between firm resources and new technologies, appropriability regimes, and corporate or environmental culture (e.g. Gomez & Vargas, 2012; Karshenas & Stoneman, 1993; Lee, Trimi & Kim, 2013; Steers et al., 2008; Yu & Tao, 2009). In contrast, firm internationalization and, in particular, GVC fragmentation as an antecedent of technology adoption[2] have largely been left unexplored despite the importance of the topic. Our development of a set of hypotheses should be seen in this light.

3.1. Internationalization and adoption of AM technologies

IB research has suggested a possible relationship between internationalization and the adoption of AM technologies (e.g. Laplume et al., 2016; Strange & Zucchella, 2018). However, the direction and magnitude of this effect are still uncertain and underexplored, and empirical evidence is lacking.

We analyze firm internationalization in terms of both intensity and geographical span. Internationalization intensity, which we measure as foreign-sales intensity, captures the firm's openness and commitment to serving customers in foreign markets (Miller et al., 2016). The firm's geographical span, which we measure as the number of countries in which the firm has activities, captures the fragmentation of the GVC across locations in multiple countries. As such, it reflects the breadth of internationalization (Goerzen & Beamish, 2003; Hitt et al., 1997; Kim et al., 1989).

On the one hand, internationalized ventures may benefit and collect insights from interactions with a diverse portfolio of clients at the global level (Keller, 2004), as international growth is assumed to be a channel through which firms can access information on new technologies from a variety of sources (Keller, 2004; Gomez & Vargas, 2012). Many

[2] It has to be noted that, at the firm level, the decisions about how to organize production across the borders and investments in technology might occur simultaneously.

IB studies argue that organizations can increase their knowledge base by sourcing technological capabilities at the global level (Cantwell, 1989; Kuemmerle, 1999). The cross-fertilization of the firm's knowledge base with external knowledge sources located in foreign countries has the potential to feed innovation processes (Malmberg & Maskell, 2002; Bathelt et al., 2004) and technology adoption (Chen et al., 2012, Cloodt et al., 2006; Hurtado-Torres et al., 2018; Singh, 2008).

On the other hand, the emergence of global factories has accelerated geographically dispersed knowledge sourcing. As value chains increasingly span national borders, global innovation networks (Narula & Guimón, 2010) have emerged. The geographical span of GVCs provides firms with culturally and cognitively diverse experiences, which drive their innovativeness and their propensity to adopt technologies owing to their access to a broad 'pool' of scientific knowledge (Griliches, 1979; Jaffe, 1986; Scherer, 1982). At the same time, a reliance on domestic and/or internal resources might lock the firm into its existing knowledge base.

Oettmeier and Hofmann (2016) argue that AM has the potential to narrow and shorten the supply chain. This technology offers the opportunity to reduce the number of subcomponents needed and, hence, the number of suppliers (Oettmeier & Hoffman, 2016). Furthermore, classical IB theory argues that knowledge is context specific (Hayek, 1945) and country specific (Bartholomew, 1997). Therefore, strong ties and embeddedness in strategic locations support the firm's access to specific technologies and increases the likelihood of their adoption. Indeed, technology adoption is particularly likely to occur in contexts characterized by shared values and a shared culture regarding innovation (Dhanaraj et al., 2004; Leonard et al., 1998; Perez-Luno et al., 2019).

Overall, we expect a firm's global presence to be beneficial for AM adoption. We thus posit the following:

Hypothesis 1. *The internationalization of the firm is positively associated with the adoption of AM technologies.*

3.2. Implications of separating R&D and production

A central issue in the present study is whether R&D activities are separated from production activities through offshoring and/or outsourcing processes. The fine-slicing of these activities has been viewed as a useful way to exploit the potential of different places and contexts (e.g. locating R&D in technological hotspots in developed regions, and outsourcing or offshoring manufacturing to emerging countries to cut costs). However, little is known about whether the fine-slicing of these activities is beneficial for capturing the overall value of innovation.

Some scholars propose that a sliced value chain in which R&D and manufacturing activities are managed by different players and/or physically distant from each other is beneficial for innovation and new technology adoption as, over time, relationships evolve towards mutual trust and partners increasingly work to add value to the relationship (Farrell, 2005; Vivek, Richey & Dalela, 2009; Steers et al., 2008). This effect is also explained using a principal-agent framework (Alipranti et al., 2015), where the principal chooses to separate R&D and production after taking degrees of control and economic efficiency into consideration.

This view has been questioned in recent years. Pisano and Shih (2009) claim that – under certain conditions – the separation of R&D and production leads to a progressive erosion of innovation capabilities. This may occur because cutting spending on basic research by offshoring R&D hampers the firm’s ability to generate sophisticated knowledge, which has been the case for many US firms. This issue emerges because knowledge-production and knowledge-spillover effects benefit from proximity and from context-specific learning processes. This is paradigmatic in the case of industrial districts, where value-chain activities are close to each other (ibid) and proximity can spawn knowledge and innovation that otherwise would not be possible because of issues associated with managing distance. Furthermore, the literature recognizes two other common disadvantages of separating R&D and production: knowledge leakage (Fisch, 2003; Sanna-Randaccio & Veugelers, 2007) and coordination costs (von Zedtwitz & Gassmann, 2002).

We argue that these divergent views should be interpreted by considering the distinction between modular and integrated systems (Lai et al., 2009). After decades in which global chains have largely been based on modular systems, digital transformation and integrated smart manufacturing systems, like AM, are driving a need for integrated bundles of tacit knowledge. Previous studies suggest that production capabilities and internal R&D are complementary in the presence of asset specificity (Ethiraj et al., 2004; Sanchez et al., 1996). However, thus far, these conditions have mainly been considered from a theoretical perspective and rarely examined empirically. AM offers an intriguing opportunity to investigate and test this framework, as it creates conditions of asset complementary between R&D and production.

Given these arguments, a critical issue relates to whether the GVC relies on modular or integrated architectures, with the former supporting a ‘softer’ separation of R&D and production. On the other hand, integrated manufacturing systems benefit from closeness between these two activities (Pisano & Shih, 2009; Zeschky et al., 2014). This phenomenon has largely been linked to industry-specific factors. In the context of this study, we adopt a different standpoint and argue that the nature of AM technologies can be ascribed to integrated systems architectures. In fact, AM pushes firms towards a different innovation culture than traditional manufacturing, which is based on rapid prototyping, agile management, and fast experimentation. As such, R&D and production are two faces of the same coin and often occur somewhat in parallel.

Furthermore, technology adoption is particularly likely to occur in those contexts in which values and culture for innovation are shared (Steers et al., 2008). Therefore, the separation of R&D from production can be detrimental to innovation, as it can interrupt idiosyncratic flows of knowledge across the innovation process – from idea generation to its industrialization.

Given these arguments, we claim that integrated production and R&D activities increase the likelihood of adopting a breakthrough technology like AM. The separation of R&D activities and production that occurs when a value chain is sliced into pieces can occur through offshoring or outsourcing. In the case of offshoring, the separation is geographical, while it is organizational if the company opts to outsource R&D, production, or both to independent third parties. Separation can also consist of both simultaneously (i.e. offshore outsourcing)[3]. Thus, we offer the following hypothesis:

Hypothesis 2. *The separation of the firm's R&D and production inhibits the adoption of AM technologies.*

3.3 The role of absorptive capacity in the separation of R&D and production

Like any managerial decision, decisions regarding the integration or separation of R&D and production are likely to be subject to contingent factors. This is even more true in the case of cutting-edge technology like 3D printing, where there is a substantial lack of recognized best practices and shared standards. For this reason, we propose that awareness of AM's potential and knowledge about this type of technology are key antecedents that give managers a different perspective when evaluating the pros and cons of separating R&D and production. In short, we argue that owing to the complexity of Industry 4.0, the implications of slicing up the

[3] Outsourcing and offshoring are different processes, but they can be combined. Outsourced activities may be undertaken by suppliers located in the same country as the lead firm (domestic outsourcing) or suppliers in foreign countries may be involved (offshore outsourcing). Offshoring can occur through offshore outsourcing or when multinational enterprises (MNE) undertake FDI and retain ownership of the offshored activities.

value chain during AM technology adoption are only evident to organizations with a certain amount of absorptive capacity. At the firm level, an organization's absorptive capacity is its ability to acquire, assimilate, and exploit external knowledge (Cohen & Levinthal, 1990). At the functional level, cross-functional absorptive capacity refers to redundancies in the expertise stemming from close linkages among function (e.g. relationships among the R&D, design, manufacturing, and marketing functions; Mansfield, 1968). Cross-functional absorptive capacity is likely to emerge in contexts where high cross-functional integration, which is defined as 'the degree of interaction, communication, information sharing, or coordination across function' (Troy, Hirunyawipada, & Paswan, 2008, p. 132), is needed. Coordination and integration across functional departments, like R&D and production, can often improve the use and value of external knowledge in the context of innovation (Foss, Laursen, & Pedersen, 2011). They can also help explain how absorptive capacity enhances new product development (Barrales-Molina, Martínez-López, & Gázquez-Abad, 2014; Clark & Fujimoto, 1987).

This is also true for technology adoption in general (Cohen & Levinthal, 1990; Gomez & Vargas, 2009; Srinivasan et al., 2002, Zahra & George, 2002), and seems to hold for Industry 4.0 (Müller et al., 2021) and the adoption of AM technologies (Oettmeier & Hofmann, 2016). As mentioned in the previous section, the nature of AM technologies can be ascribed to integrated systems architectures in which R&D and production often occur somewhat in parallel. It is reasonable to argue that those firms that have been able to acquire enough knowledge about AM technologies should be aware of the benefits and risks stemming from the integration or separation of the two functions.

We therefore argue that a capacity to assimilate and exploit knowledge related to AM technologies can enable a firm to recognize the negative effects of the separation of R&D and production. In other words:

Hypothesis 3. *A firm's absorptive capacity in terms of AM-specific know-how negatively moderates the likelihood of the firm separating R&D and production.*

4. METHODS

We test the above hypotheses using a proprietary cross-industry database covering 197 companies in various countries. We consider both adopters and non-adopters of technology as well as domestic and international companies, and control for these differences. Our dependent variable is investments in AM technologies and we use a Tobit regression as our analytical procedure. We chose this technique because many of the sample firms reported no investments in AM, leading to left-censoring of the dependent variable.

4.1 Sampling procedure

First, we gathered a sample of 800 companies with AM activities through in-depth examinations of newspapers and magazines (using the LexisNexis database). We controlled for sample distribution in terms of industry and size using reports about the diffusion of AM, such as the 3D Printing Wohlers Report, or by considering data from Statista.com. To further check he sample's reliability, company information and contact details were gathered from the Orbis database (Bureau Van Dijk) and from publicly available sources. Similar sampling procedures have been adopted in numerous management studies (Cho *et al.*, 2018; Corsino *et al.*, 2019; Reardon *et al.*, 2017).

The firms in the sample received a structured questionnaire that included questions regarding our chosen variables (see section 4.3). We received 197 usable responses (response rate = 12.3%). Direct interactions and reminders were crucial for increasing the response rate. To further increase the response rate, we promised to provide respondents with information on our findings in the form of basic descriptive statistics. Prior to distributing the questionnaire to the companies in our sample, we pretested it on an ad hoc focus group, which included carefully selected managers and experts in AM, and on a group of international operations managers. Based on these pre-tests, we refined the questionnaire where necessary.

4.2 Sample composition and descriptive statistics

The final database of 197 observations includes 69 adopters of 3D printing technologies (35%), 132 firms with foreign sales (67%), and 79 multinational companies (40%), which we define as firms with facilities and assets in at least two countries. In terms of size, the sample consists of 75 small firms (38%) with less than 50 employees, and 97 large companies (49%), defined on the basis of the European Commission's threshold of at least 250 employees.

Tables 1 and 2 report the sample distributions in terms of regions (we have aggregated countries into six major geographical areas, i.e. Western Europe, Eastern Europe, US, South America, Asia and Middle East, and other), and industries. About half of the sample consists of firms headquartered in Western Europe (see Table 1). Roughly 25% of the companies in the sample are located in Eastern Europe, while the rest of the firms are incorporated in the US, South America, Asia, or the Middle East. Overall, the sample is fairly balanced in terms of firms from developed and developing or emerging economies. As shown in Table 2, 27.9% of the companies in the sample are active in the electronics industry, 18.3% are in the machinery industry, 17.3% are in the chemical industry, and 10% are in manufacturing. The rest of the sampled firms belong to construction (9.6%), automotive and aerospace (6.6%), transportation (6.6%), and other industries (3.6%).

Table 1. Sample composition – regions (headquarters)

Western Europe	53.8%
Eastern Europe	24.9%
US	6.1%
South America	6.6%
Asia and Middle East	5.6%
Other	3.0%

Total	***100.0%***

Table 2. Sample composition – industries

Electronics	27.9%
Machineries	18.3%
Chemical	17.3%
Manufacturing (other)	10.2%
Construction	9.6%
Automotive and aerospace	6.6%
Transportation	6.6%
Others	3.6%
Total	***100.0%***

4.3 Dependent and independent variables

Table 3 presents details on our dependent and independent variables. Our dependent variable is the extent of investments in AM technology from 2012 to 2015. We considered investments in AM aimed at supporting the following activities: R&D, prototyping, production, and logistics. The variable was operationalized using a Likert scale with values from 0 to 5 as reported in table 3.

We asked our respondents to provide us with the absolute value of the firm's investments in AM technologies instead of a ratio, as we targeted the *first* adoption of AM technologies and owing to the significant presence of small and medium sized enterprises (SMEs) (51%). This choice is consistent with previous comparable studies (Yu & Tao, 2009). The absence of a correlation between AM and firm size (see Table 4) confirms the reliability of this method.

We employ the following independent variables:

- Internationalization of the firm, measured as foreign-sales intensity and as the number of countries in the firm's value chain.
- Geographical separation of R&D and production activities, meaning whether these activities are located in separate countries.
- Organizational separation of R&D and production activities, meaning whether these

activities are governed by one (or more) companies that are legally independent from the sample firm through outsourcing processes, regardless of whether these activities take place in the home country or a foreign country.

We take a number of control variables into account:

- Firm size,
- Country in which the firm's headquarters are located,
- Industry in which the firm operates,
- Type of country in which R&D is located (developed versus emerging),
- Type of country in which production is located (developed versus emerging),
- R&D intensity,
- Foreign-sales intensity, and
- Awareness about the potential of AM technologies.

Table 3 provides details on the definitions of these variables. Table 4 presents the descriptive statistics and correlations. As the correlations among variables are fairly small, the risk of multicollinearity is limited. As expected, we found a significant correlation between firm size and the number of countries in which the company operates, as well as between geographical and organizational separation of R&D and production activities.

Table 3. Variable definitions (omitting countries and industry dummies)

Variable	**Description**	**Definition**	**Variable type**
Dependent variable			
AM	Amount of investments in 3D printing, 2012-2015	0 = no investments in AM 1 = investments in AM between EUR 0 and EUR 10,000 2 = investments in AM between EUR 10,001 and EUR 50,000 3 = investments in AM between EUR 50,001 and EUR 200,000 4 = investments in AM between EUR 200,001 and EUR 500,000 5 = investments in AM of more than EUR 500,000	Ordinal, range: 0-5
Independent variables			
Foreign_sales	Foreign-sales intensity	0 = 0% 1 = 1-20% 2 = 21-40%	Ordinal, range: 0-5

		3 = 41-60% 4 = 61-80% 5 = 81-100%	
NCountries	Metric focused on fragmentation of GVC across different countries	Number of countries across which the value chain is sliced	Number
LOCSEP	Geographical separation of R&D and production activities	0 = R&D and production are in the same country 1 = R&D and production are in different countries	Binary
ORGSEP	Organizational separation of R&D and production activities	0 = R&D and production are governed by the company 1 = R&D and/or production are outsourced to independent third parties	Binary
Control variables			
SIZE	Firm size	Log(employees)	
Holding	Whether the company belongs to a group of companies	0 = independent company 1 = part of a group	
RD_exp	R&D intensity	1 = < 5% of revenues 2 = 5 -10% of revenues 3 = 10 - 15% of revenues 4 = 15 - 20% of revenues 5 = >20% of revenues	Ordinal, range: 1-5
RDDEV	Location of R&D in developed countries	0 = the company does not have R&D activities in developed countries 1 = the company has R&D activities in developed countries	
RDEM	Location of R&D in emerging countries	0 = the company does not have R&D activities in emerging countries 1 = the company has R&D activities in emerging countries	
PRODDEV	Location of production in developed countries	0 = the company does not have production activities in developed countries 1 = the company has production activities in developed countries	
PRODEM	Location of production in emerging countries	0 = the company does not have production activities in emerging countries 1 = the company has production activities in emerging countries	
KNOW3D	Awareness and understanding of AM potential	0 = none 1= low (no particular actions have been taken by the company) 2 = medium (basic information/individual expertise/unstructured knowledge) 3 = good (e.g. some training initiatives, or participation in workshops or fairs) 4= high (e.g. investments in know-how, in-sourcing of competences, hiring of specialists, investments in start-up)	Ordinal, range: 0-4

Table 4. Descriptive statistics and correlations (country and industry dummies omitted)

	Variable	**Mean**	**Std. Dev.**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
(1)	AM	0.746	1.335								
(2)	SIZE (log employees)	5.311	2.014	-0.0007							
(3)	Holding	0.178	0.383	0.0188	0.0128						
(4)	RD_exp	2.142	1.418	0.0623	-0.0654	-0.0655					
(5)	KNOW3D	1.421	1.464	0.6111 ***	-0.323 ***	0.0478	0.0816				
(6)	Foreign_sales	1.787	1.728	0.2507 ***	0.0326	-0.0041	0.1395 *	0.1224 *			
(7)	NCountries (log value)	0.520	0.709	0.0699	0.1639 **	0.0206	-0.072	0.0043	0.3381		
(8)	LOCSEP	0.076	0.266	-0.0315	0.0923	-0.0333	0.0794	-0.1222 *	0.0355	0.2965	
(9)	ORGSEP	0.239	0.427	-0.0811	-0.0143	-0.0421	0.129 *	-0.0718	0.014	0.0908	0.1536 **

5. RESULTS

As we looked for converging evidence, we empirically explored our theoretical arguments using a set of descriptive statistics and a Tobit regression analysis.

5.1. Descriptive statistics

First, we investigated the relationship between technology adoption and the firm's internationalization by considering foreign-sales intensity and the span of activities located abroad. The degree of advanced manufacturing investments within organizations shows foreign activities (AM = 0.90) to be roughly twice than that of domestic firms (AM = 0.43). This is a significant difference, as confirmed by the t-test (Pr(|T| > |t|) = 0.0196). Similarly, organizations reporting AM activities have a foreign-sales intensity that is 51% higher than firms without investments in AM (foreign sales = 2.37 and foreign sales = 1.56, respectively). This is also a significant difference (Pr[|T| > |t|] = 0.0033). The correlation between AM investments and foreign sales is also relevant and significant (0.2507; p-value < 0.001), which confirms the previous insights. Interestingly, the correlation between foreign sales and expertise in AM (KNOW3D) is even higher at 0.6111 (p-value < 0.001).

We uncover different findings with respect to the breadth of internationalization. Table 5 shows the variation in AM activities in relation to the number of countries in which companies operate. Three groups are used to distinguish among, at the extremes, purely domestic companies and those with finely sliced value chains (i.e. the 10% of the firms in our sample with activities in at least five countries). Our findings suggest an inverse U-shaped relationship, indicating the possibility of an optimal number of countries for 3D printing businesses. In short, the effects of distributing the value chain across several countries on AM adoption is uncertain, as also suggested by the non-significant correlation between the two variables (0.0699; p-value > 10%). Additional analyses are needed in this regard.

Table 5. AM activities and international span

	Number of countries		
	1 (60% of the sample)	2-5 (30% of the sample)	> 5 (10% of the sample)
AM investments (0-5)	0.653	1.045	0.563
% of companies with AM activities	24.6%	34.1%	25.0%

Table 5 shows the differences in AM adoption between organizations with and without separate R&D and production activities. Analyses 'a' and 'b' explore the effects of the geographical and organizational separation of at least one of these activities. T-tests suggest that differences at this level are weakly significant and/or uncertain in the case of organizational separation, and non-significant in the case of geographical separation. However, in all four cases, AM activities are more pronounced when R&D and production are coupled together, spanning a range of 26% (minimum difference) to 57% (maximum difference) as AM investments increase. These differences become statistically significant when considering the effect on R&D and production outsourcing (see analyses 'c' and 'd'). This evidence reinforces the assumption that AM pushes the organization towards new processes of innovation and experimentation in which R&D and production are merged together, thereby blurring their boundaries.

Table 6. Adoption of AM technologies and separation of R&D and production

		% of organizations with AM activity	Intensity of AM investments (0-5)
(a) Geographical separation of R&D and production	With (different county)	20.0%	0.60
	Without (same country)	28.0%	0.76
	T-test	*Pr(|T| > |t|) = 0.5057*	*Pr(|T| > |t|) = 0.6602*
(b) Organizational separation of R&D and production	With (independent organizations)	19.1%	0.55
	Without (same country)	30.0%	0.80
	T-test	*Pr(|T| > |t|) = 0.1471*	*Pr(|T| > |t|) = 0.2571*
(c) R&D	In-house	30.2%	0.82
	Outsourced	8.0%	0.20
	T-test	*Pr(|T| > |t|) = 0.0198*	*Pr(|T| > |t|) = 0.0282*
(d) Production	In-house	31.9%	0.86
	Outsourced	17.7%	0.50
	T-test	*Pr(|T| > |t|) = 0.0394*	*Pr(|T| > |t|) = 0.0794*

5.2. Regression analysis

Table 7 shows the outcomes of the regression analysis based on a Tobit model. Model 1 reports the results related to only the control variables. They indicate that AM is most often adopted by those firms active in the machinery sector and, above all, the automotive and aerospace industries. This is consistent with the findings of earlier studies (Dwivedi et al., 2017; Gebler et al., 2014; Kannattukunnel, 2016). As expected, the likelihood of AM adoption is lower for those firms originating from less-developed countries, such as those in Eastern Europe. We also find a significant relationship between investments in AM and awareness of AM’s potential (‘KNOW3D’), which serves as an initial confirmation of the relevance of the absorptive capacity argument in shaping the focal dynamics.

Model 2 investigates our first hypothesis, which proposes that the internationalization of the firm is positively associated with the adoption of AM technologies. As mentioned in the theoretical section, we account for two aspects of internationalization: commitment to foreign customers, measured as foreign-sales intensity (Foreign sales), and breadth, measured as the span of the firm’s activities abroad (NCountries). Foreign-sales intensity is strongly associated with investments in AM (coefficient = 0.367; p-value < 0.01), while we do not find a similar significant effect for breadth of the GVC (i.e. firms with activities located in several countries). In sum, we find AM to be related to only some aspects of firms’ internationalization.

Models 3 and 4 study the effects on AM of geographically separating R&D and production into different countries (LOCSEP), and of separating them from an organizational standpoint by outsourcing one or both of the activities (ORGSEP). According to the results of the regression in Model 3, Hypothesis 2 is rejected. More specifically, neither the geographical separation nor the organizational separation of R&D and production are associated with the adoption of AM technology.

We further develop this outcome in Model 4 by examining whether absorptive capacity is needed to appraise the implications of separating R&D and production when AM investments are made, as stated in Hypothesis 3. This is evident in the case of geographical separation: the coefficient of LOCSEP is significant and negative, while the moderator LOCSEP_KH (equal to LOCSEP*KNOW3D) is significant and positive. Therefore, the above-mentioned effect of KNOW3D is inverted – when R&D and production are geographically separated, the higher the firm's absorptive capacity, the lower its investments in AM. We do not find a similar relationship for organizational separation (i.e. the outsourcing of R&D and/or production).

Finally, in Models 5 and 6, we explore whether effects of organizational separation, which we have thus far found to be irrelevant for strategic decisions on AM as an aggregate construct, emerge if we split the ORGSEP variable into its two components: outsourcing of R&D (OUTRD) and outsourcing of production (OUTPROD). Therefore, we dropped the composite variable ORGSEP in Models 5 and 6. This analysis reveals an unexpected finding: the separation of R&D and production work differently in the two cases. First, the outsourcing of R&D inhibits the adoption of AM technology. Second, the firm's absorptive capacity in terms of AM-specific know-how negatively moderates the likelihood that a firm will outsource production.

Table 7. Regression analysis[4]

Dependent = AM	1	2	3	4	5	6
SIZE	0.116	0.0727	0.0726	0.0558	0.0553	0.0237
	(0.0980)	(0.0991)	(0.0990)	(0.100)	(0.0975)	(0.0963)
WEu	-0.956	-0.942*	-0.942	-1.084*	-0.895*	-1.130**
	(0.705)	(0.539)	(0.570)	(0.560)	(0.531)	(0.541)
EastEU	-2.484***	-2.338***	-2.333***	-2.540***	-2.346***	-2.591***
	(0.805)	(0.657)	(0.683)	(0.679)	(0.646)	(0.664)
US	-0.363	0.0416	0.0557	-0.142	0.122	-0.181
	(0.917)	(0.786)	(0.805)	(0.827)	(0.792)	(0.811)
SouthAmerica	-0.649	-0.0959	-0.0938	-0.252	-0.0529	-0.462
	(0.936)	(0.767)	(0.785)	(0.779)	(0.777)	(0.753)

[4] Base categories are: a) other countries (e.g. African countries) and b) other industries (e.g. scientific R&D).

AsiaME	-2.858*	-2.384*	-2.382*	-2.515*	-2.104	-2.302*
	(1.465)	(1.294)	(1.295)	(1.329)	(1.339)	(1.308)
HiTech	0.643	0.571	0.572	0.710	0.650	0.793
	(0.576)	(0.559)	(0.567)	(0.593)	(0.576)	(0.587)
Chem	0.286	-0.0260	-0.0273	-0.0928	-0.120	-0.191
	(0.629)	(0.585)	(0.578)	(0.591)	(0.571)	(0.589)
Machineries	0.885	0.528	0.531	0.442	0.426	0.248
	(0.564)	(0.544)	(0.551)	(0.558)	(0.554)	(0.561)
Manufacturing (other)	0.246	-0.0258	-0.0254	0.0935	0.213	0.413
	(0.676)	(0.652)	(0.650)	(0.656)	(0.633)	(0.604)
AutoAero	0.983*	0.919	0.917	0.955	0.895	0.888
	(0.576)	(0.577)	(0.573)	(0.585)	(0.582)	(0.588)
Transportation	0.0757	-0.0615	-0.0667	-0.176	-0.0854	-0.129
	(0.685)	(0.617)	(0.635)	(0.684)	(0.662)	(0.697)
Construction	-0.148	-0.0928	-0.0947	-0.111	0.137	0.0885
	(0.799)	(0.811)	(0.813)	(0.813)	(0.748)	(0.733)
Holding	0.168	0.102	0.100	0.119	0.0211	0.187
	(0.509)	(0.490)	(0.490)	(0.488)	(0.479)	(0.466)
RD_exp	-0.100	-0.152	-0.152	-0.145	-0.166	-0.196
	(0.145)	(0.151)	(0.153)	(0.149)	(0.158)	(0.155)
Know3D	1.243***	1.202***	1.201***	1.223***	1.126***	1.258***
	(0.135)	(0.134)	(0.136)	(0.146)	(0.135)	(0.149)
Foreign_sales		0.343***	0.343***	0.351***	0.352***	0.396***
		(0.0944)	(0.0945)	(0.0966)	(0.0942)	(0.0978)
NCountries		0.00903	0.0133	0.105	0.0766	0.0875
		(0.230)	(0.244)	(0.245)	(0.244)	(0.234)

LOCSEP			-0.0566	-2.492*	-3.013*	-3.868**
			(0.687)	(1.294)	(1.727)	(1.892)
ORGSEP			0.000728	0.670		
			(0.432)	(0.695)		
LOCSEP_KH				1.290*	1.921**	2.394***
				(0.670)	(0.896)	(0.914)
ORGSEP_KH				-0.316		
				(0.348)		
Out_RD					-2.095**	-2.020**
					(1.026)	(0.838)
Out_Production					0.0991	1.215*
					(0.434)	(0.654)
OutP_KH						-0.608**
						(0.295)
Constant	-2.248**	-2.394**	-2.391**	-2.321**	-2.109**	-2.041**
	(1.134)	(1.029)	(1.049)	(1.035)	(0.994)	(0.985)
Observations	197	197	197	197	197	197
Pseudo R^2	0.253	0.275	0.275	0.283	0.295	0.303

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

6. DISCUSSION

Our study sheds new light on the relationship between internationalization and technology adoption. On the one hand, this interplay is beneficial for the firm. The exposure to international markets drives the company to innovate. We find a strong association between foreign-sales intensity and investments in AM. On the other hand, the same effect is not evident when it comes to another aspect of internationalization – the firm's international span (i.e. the number of countries in which it operates). Therefore, findings at this level are uncertain.

Our analysis leads to a more fine-grained understanding of the assumption underpinning Hypothesis 1 – the adoption of AM technologies is positively associated with the internationalization of the firm, but only if the latter is measured in terms of intensity (i.e. as foreign sales to total sales). We interpret this outcome as follows. The internationalization of the firm in terms of foreign sales supports innovation processes, as it exposes the organization to new perspectives (Bathelt et al., 2004; Keller, 2004; Gomez & Vargas, 2012; Malmberg & Maskell, 2002) and pushes it to evolve in response to the challenges it encounters in new foreign markets, which are characterized by different customers, cultures, institutions, and technological bases (Chen et al., 2012, Cloodt et al., 2006; Hurtado-Torres, 2018; Singh, 2008). Nevertheless, some aspects of the firm's internationalization do not seem to have any effect or, at the extreme, are detrimental to 'phygital' technologies (i.e. those at the crossroad between physical and digital; e.g. additive manufacturing). In particular, and in contrast with the mainstream view, we posit that under certain conditions the adoption of a new technology, such as AM, is impeded by finely sliced global value chains (H2). This type of fragmentation unfolds as a dispersion of the firm's activities across several countries and/or as a separation of critical innovation activities, with R&D on the one side and production on the other.

Our empirical results include unexpected findings at this level as well, which confirm some theoretical arguments and suggest a need to revise others. AM investments are more pronounced when R&D and production are coupled together. However, patterns of interaction work differently than we surmised. Our empirical findings do not support the assumption that the separation of the firm's R&D and production per se affects the adoption of AM technology. Therefore, H2 in its original formulation is rejected. However, our results vary when we distinguish between geographical and organizational forms of separation, and between the specific roles of R&D and production. First, the firm's absorptive capacity 'activates' the geographical-separation effect – if the company has expertise in AM technology, it tends to locate R&D in the same country as production. Second, organizational separation is sensitive to the type of activity being outsourced. Specifically, the outsourcing of R&D inhibits the adoption of AM technology, while the same is true for production only if the company has absorptive capacity. In other words, the need to keep R&D in-house is generally accepted, while a well-developed 'AM capability' supports merging R&D and production into a unified process, as stand-alone production in the GVC does not seem beneficial.

These findings suggest that when a firm offshores R&D or production but maintains ownership and governance of these activities, it will struggle to reap the benefits usually derived from outsourcing, such as the opportunity to free up internal resources that could be effectively used for other purposes (Asmussen, 2009). The dispersion of GVCs complicates the coordination of the involved units, thereby reducing opportunities to leverage complementary assets in the innovation process (Buckley, 2009; Laplume et al., 2016; Strange et al., 2017) and, consequently, impeding the formation of innovation capabilities (Pisano & Shih, 2009). The above-mentioned dynamics in the case of offshoring are enforced by the nature of the knowledge, which tends to be context specific (Hayek, 1945) and country specific (Bartholomew, 1997).

Given this evidence and our inferences, complementary assets arising from the interplay between R&D and production have significant merit in explaining the relationship between process innovation and internationalization. The decision-making complexity associated with the introduction of breakthrough innovations is exacerbated by the joint interaction of decisions regarding sliced or integrated production, sliced or integrated R&D, and the geographical location of these activities.

7. CONCLUSIONS

Our study contributes to the literature at the intersection of internationalization and innovation, and addresses a gap in our knowledge pertaining to the roles of internationalization and GVC configuration in the innovation capacity of the firm. We applied and tested the theoretical framework of 'complementary assets', which we adapted to a GVC context and revised to account for emerging features of contemporary scenarios, as suggested by some anecdotal evidence.

As a novel contribution, our theoretical arguments and findings converge to highlight a 'double-faced' effect of internationalization on the advancement of manufacturing technologies. On the one hand, internationalization is beneficial because it implies openness to new markets and customer needs. On the other, the international fragmentation of the value chain gives rise to new challenges and risks owing to the separation of R&D and production. Only under certain conditions can firms fine-slice their value chains without harming their innovation capacity. The separation of R&D and production is risky or even counterproductive, as it can mitigate the positive effect of complementary assets. We find that only those firms that have a certain level of absorptive capacity in relation to AM are able to leverage these dynamics.

Separation can be conceived as a symmetrical concept – if R&D is geographically or organizationally distant from production, then production is also distant from R&D. This is why we conceptualize ‘separation’ between R&D and production as a multifaceted and subtle concept. However, our findings show that the separation of these two value-chain activities has asymmetrical effects that vary depending on what is offshored / outsourced. In other words, separation is sensitive to the type of activity being subject of this decision.

The theoretical implications of our study are important because they should lead to the rethinking of constructs and models regarding how a GVC is decoupled and/or assembled. The managerial implications are also important, as our findings offer guidance to organizations for adjusting their GVCs following investments in AM. Moreover, policy-makers need to pay attention to these dynamics, especially when the goal is to stimulate offshoring/reshoring processes and to restore competitiveness through novel paradigms of geopolitical innovation.

8. LIMITATIONS AND FUTURE RESEARCH

This study should be evaluated in light of its boundaries. The first limitation is found in the limited number of factors that we took into consideration when assessing the likelihood of AM technology adoption among our sampled firms. As we have emphasized, we mainly focused on the span of internationalization and geographical/organizational separation of R&D and production activities as factors influencing AM adoption. Future studies should assess the adoption of AM technologies in relation to a wider range of factors related to the configuration of the firm’s international value chain.

Another limitation of our study is our narrow focus on additive manufacturing. Future studies should assess the adoption of other Industry 4.0-related technologies, such as the Internet of Things, robotics, and artificial intelligence.

Furthermore, a larger sample size is desirable for generating more robust results. Moreover, panel data is needed to better understand causal relationships among the variables,. Future research should also consider collecting data to not only distinguish between production and R&D activities but also allow for consideration the configuration of other low-/medium-/high-value-added activities.

Finally, future research could advantageously investigate the dynamics of adopting AM technologies and other Industry 4.0-related technologies. Such research should, perhaps, more carefully distinguish among factors and determinants in developed and emerging economies and compare large and small firms.

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