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Assessing the effect of 3D printing technologies on entrepreneurship: An exploratory study

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ABSTRACT

The aim of this paper is to critically assess the effect of 3D printing technologies on entrepreneurship. While 3D printing technologies (also known as 'additive manufacturing') have been considered as highly transformative technologies, they have been so far (despite over 30 years of existence) restricted to niche markets, and until recently, it seemed that only the largest firms were able to take advantage of those technologies. However, the cost of use of such technologies has sharply decreased over the past few years, and an increasing number of service companies offer both offline (Fab Labs, makerspaces, bureaus) and online (3D printing platforms) access to 3D printing capacities, enabling to "bridge the gap" and provide access to 3D printing technologies to everyone.

In this context, using a case-based exploratory methodology, this research aims to explore the benefits of 3D printing technologies for entrepreneurs and new ventures, in particular in relation to overcoming specific challenges these smaller and younger structures face. After identifying the key types of hurdle faced by entrepreneurs – NPD issues, technical issues, market issues, financial issues, and business model issues – this article investigates the manner in which different forms of usage of 3D printing technologies – prototyping, tooling, direct manufacturing, distributed and localised manufacturing – can help alleviate each of those types of barrier.

The results of this research indicate that 3D printing technologies are indeed likely to enable entrepreneurs to overcome the five main types of barriers they generally face. Furthermore, because of the very particular situation of entrepreneurs and new ventures and the specific challenges they face in terms of scale, access to markets, and lack of financial resources, 3D printing may in fact be more transformative for smaller and younger structures, than for larger and well-established corporations. However, this research also indicates that benefits for entrepreneurs derived from the use of 3D printing may depend on the degree of involvement of 3D printing in the overall productive process – the more the merrier – and that using 3D printing only at design and tooling stage, although helpful to some extent, may not be so impactful.

1. Introduction

"Transformative technology of the 2015–2025 period" for Rich Karlgraad (Forbes) (Karlgraad, 2011), 3D printing[1] is considered as one of the key drivers of an ongoing "fourth industrial revolution"(Herweijer et al., 2017; Markillie, 2012; Schmitz et al., 2019). In this respect, then U.S. President, Barack Obama, noted in his 2013 State of the Union address,[2] that "3D printing [had] the potential to revolutionise the way we make almost everything." Foreseeing a widespread usage of 3D printing in our everyday life, Chris Anderson (then Wired magazine editor-in-chief), even hypothesised that the "desktop manufacturing revolution [would] change the world as much as the personal computer did" (Anderson, 2012).

It is true that in some industries, the "revolution" has already begun. In the medical sector, for instance, 3D printing has already become the most prevalent manufacturing technology in the case of prosthetics (e.g. bone and cartilage replacements), dental implants and hearing aids (Davies, 2013; Petrick and Simpson, 2013; Sandström, 2016; Wohlers, 2020). In other industries, e.g. in the aerospace and automotive sectors, a growing number of major players have adopted 3D printing beyond

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1 Or "additive manufacturing", as it is sometimes referred to in more "industrial" contexts.
2 https://obamawhitehouse.archives.gov/photos-and-video/video/2013/02/12/2013-state-union-address-0

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prototyping to directly manufacture end-use parts and products—Airbus, Ford, General Electric are just a few of many companies that make a significant use of 3D printing technologies.

Yet, the changes brought about by 3D printing technologies are not restricted to multinationals and large corporations. As noted in Rayna et al. (2015), the sharp decrease in the price of the 3D printers and the emergence of online 3D printing platforms have provided means for any firm – no matter how small – to make use of 3D printing technologies. Besides having an effect on "traditional" entrepreneurs, Troxler and Wolf (2017) and Hamalainen and Karjalainen (2017) note that 3D printing technologies are conducive to hobbyist becoming entrepreneurs (in particular through the use of 3D printing platforms as brokers). In fact, as emphasised in Nambisan (2017), new digital technologies, such as 3D printing, because they transform the nature of uncertainty associated with entrepreneurial processes and the way to address this uncertainty, open important research questions at the nexus of digital technologies and entrepreneurship that "call for careful consideration of digital technologies and their unique characteristics in shaping entrepreneurial pursuits".

Indeed, the question remains as to what the particular benefits of using 3D printing technologies are for entrepreneurs and, more specifically, how it can help overcome barriers faced by entrepreneurs. This is precisely what this paper intends to investigate. In order to avoid the traditional pitfalls, when it comes to the impact of new technologies, of being either too enthusiastic or too sceptical, this research focuses on the different kinds of usage of the technology, rather than the technology itself.

The methodology adopted is exploratory and relies on multiple case studies, in accordance with case study research (Chavez et al., 2017; Eisenhardt and Graebner, 2007; Yin and Thousand Oaks, 2003). Cases were selected to reflect characteristics and problems identified in the conceptual frameworks used in this research, with the aim to provide a comprehensive understanding of the changes, based on types of usage, brought by 3D printing technologies on challenges faced by entrepreneurs.

This paper begins with an extensive literature review enabling to identify the various types of challenges traditionally faced by entrepreneurs. The second part provides a brief overview of 3D printing technologies, as well as their comparative advantages in regard to traditional manufacturing techniques. The following section focuses on detailing the different types of usage of 3D printing technologies, while the final section, investigates how the particular characteristics of these new technologies can help overcome traditional barriers and challenges related to entrepreneurship.

2. Literature review

As a research field, entrepreneurship has been largely transformed in the past decade by the emergence of new theoretical perspectives aiming to explain the actions and logic that underpin entrepreneurial behaviour (Fisher, 2012). In particular, the introduction of the effectuation theory in the seminal work of Shane and Venkataraman (2000) and Sarasvathy (2001) has arguably caused a "paradigm shift" in entrepreneurial research (Perry et al., 2012). Contrasting with the "traditional" view of entrepreneurs as aiming to find means to achieve a particular predefined end (causation), the "effectuation" view instead argues that entrepreneurs mainly define "ends" based on existing means at their disposal (Sarasvathy, 2001; Shane and Venkataraman, 2000). Other emerging theories, such as the cognitive (Baron, 2004; Mitchell et al., 2007) and "bricolage" (Baker and Nelson, 2005) perspectives also emphasise the procedural nature of entrepreneurial actions.

The role of new technologies in relation to entrepreneurship has been also discussed in the recent literature (Giones and Brem, 2017; Kraus et al., 2018; Mohsen et al., 2020; Nambisan, 2017), not only because new ventures and entrepreneurs often play a critical role in the diffusion of those technologies, but also because new technologies are often powerful enablers of entrepreneurship by fostering opportunities and decreasing barriers (Nambisan, 2017). In the case of 3D printing technologies, literature related to entrepreneurship has so far mainly focused on entrepreneurial issues and opportunities within the 3D printing industry itself, e.g. in the relation to open source hardware (Ferdinand and Ferdinand, 2018; Greul et al., 2018; Kwak et al., 2018; West and Kuk, 2016) or 3D printing services (Holzmann et al., 2017; Rayna et al., 2015). In regard to the benefits of 3D printing for the "outside world", another stream of literature focuses on how makerspaces and fab labs (where 3D printers are located) can be conducive to entrepreneurship (Browder et al., 2019; Mortara and Parisot, 2018; 2016; Rayna and Striukova, 2019; 2020). Finally, several recent articles discuss how advances in 3D printing technologies can lead to creation of new entrepreneurial opportunities due to the localisation of production and to the development of consumer demand (Bonfanti et al., 2018; Elia et al., 2020; Jiang et al., 2017; Laplume et al., 2016; Ner and Siemsen, 2017; Rath et al., 2019), as well as to creation of new opportunities in the area of academic entrepreneurship (Monllor and Soto-Simeone, 2019; Rippa and Secundo, 2019; Secundo et al., 2020).

However, besides the (important) issue of *new* entrepreneurial opportunities arising from 3D printing technologies, lies the more general (and arguably more critical) question of whether – and to which extent – these technologies could be used to help exploit *existing* opportunities, by alleviating barriers and hurdles traditionally faced by entrepreneurs and new ventures. This is the main goal of this research and in order to address this question in a comprehensive and systemic manner, the following paragraphs aim to outline the key barriers and limitations to entrepreneurial action identified in the literature are reviewed in the following paragraphs.

Miller (1983) defines an entrepreneurial firm as a firm involved in new entry, i.e. entering new or established markets with new or existing products (Lumpkin and Dess, 1996). Though numerous ventures are founded every year around the world, their survival rate is low, as only two in eight will still exist after five years (Feinleib, 2011; Song and Di Benedetto, 2008). In fact, only one in 10 venture-backed startups generate meaningful returns (Feinleib, 2011).

Looking at the literature, the low survival rate of new entrepreneurial ventures can be explained by five main types of entrepreneurial challenge: (1) New Product Development (NPD) issues, (2) technical issues, (3) market issues, (4) financial issues, and (5) business model issues.

Regarding the first issue, survival of entrepreneurial firms generally requires successfully introducing new products (Marion et al., 2012; Nevens and Uttal, 1990). As such new products contribute to firms' growth and profitability, help companies build reputation and brand, and attract financial and human resources (Blundell et al., 1999; Crawford, 1987; Nevens and Uttal, 1990). While arguably important for any firm, NPD is simply critical for entrepreneurs, as it is directly linked to the survival of new firms (Marion et al., 2012) and their ability to gain a share of the market (Aspelund et al., 2005). Logically, new ventures and entrepreneurs are significantly more dependent on NPD than established firms, as all their products are, by definition, new and they do not have a lifeline of existing products to rely on if the new ones fail (Schoonhoven et al., 1990).

However, new product development is, generally speaking, a complex and difficult task (Balachandra and Friar, 1997). The rate of failure of new products, especially in consumer markets, is not only traditionally very high (Crawford, 1987), but has been getting even higher: whereas in the 1980s only 35% to 67% of new products failed (Booz and Hamilton, 1982; Cooper and De Brentani, 1984), this figure has progressively increased to up to 95% (Berggren and Nacher, 2001). In this context, entrepreneurs and new ventures are obviously not any better than well-established firms, but a further issue they face is that, for them, successful market entry generally means introducing disruptive products (Feinleib, 2011), which entails significantly more risk, as more innovative products fail more often than less innovative ones (Freeman and Soete, 1997; Mansfield, 1981). Unlike established businesses, incremental innovation is seldom an option for entrepreneurs and new ventures.

NPD issues faced by entrepreneurs are often further amplified by a second type of challenge they have to overcome: technical issues. Indeed, technical resources are critical to successfully develop new products (Cooper, 1983; Cooper and De Brentani, 1984; Kulvik, 1977). Unfortunately, entrepreneurs often lack both technical skills—e.g. ability to screen a concept for technical feasibility, create and test a prototype, and pilot production—and access to technical resources—e.g. production resources, skills of staff, experience in research and development (Rothwell, 1978),which are even scarcer in the case of new ventures (Song et al., 2010). Generally speaking, even when 'successfully developed', new products are prone to being defective (Cooper, 1979; Hopkins and Bailey, 1971), may lack critical features or be technically flawed (Crawford, 1987; Fields et al., 2003; 2004), because of poor in-house prototype testing, inadequate prelaunch testing, production costs running higher than expected, and problems arising during manufacturing (Hopkins and Bailey, 1971). While any business may encounter such kinds of issues (even the largest and best-known companies have to face 'productgates' from time to time and organise recall), new ventures are not only more likely to experience technical issues, but are also more inclined to tolerate them, because they have to do 'more with less' (Azadegan et al., 2013). Furthermore, failed product development is particularly detrimental to young entrepreneurial ventures, as unless problems are fixed immediately, customers may lose interest in the new product and might no longer be eager to purchase the product when the 'perfect' version of the product is finally released (Feinleib, 2011).

Even when entrepreneurs are in a position to develop new products successfully and overcome technical issues, they are likely to face market-related challenges, as even a well-developed product may simply not correspond to what customers want (Crawford, 1987). While any business may experience such issues – understanding (Abetti, 1986; Fields et al., 2003; 2004; Rangan, 1994) and meeting customers' expectations (Hauser et al., 2006; Ogawa and Piller, 2006; Schilling and Hill, 1998), needs and usages (Berggren and Nacher, 2001; Phua and Jones, 2010; Ziamou, 2002) has been known to be challenging even for 'market leaders' – entrepreneurs, unlike more mature firms, often do not have formal structures or professionals to assist them with market-related strategies (Phua and Jones, 2010). In fact, customers may not be aware of their own needs (von Hippel, 1988) – even more so in the case of new technologies, often borne by startups and entrepreneurs – and while this may be in itself a source of entrepreneurial opportunities (Bao et al., 2020; Shane and Venkataraman, 2000), this also means that the limited and traditional marketing research methods entrepreneurs usually have at their disposal may simply not 'do the trick' (von Hippel, 2005; O'Hern and Rindfleisch, 2010).

As a matter of fact, product failure is often linked to poor market research (Hopkins, 1980; Hopkins and Bailey, 1971), inadequate market analysis (Cooper, 1979; Hopkins and Bailey, 1971; Rubenstein et al., 1976), products being developed in the absence of market information (Jolly, 1997) and without a clear market need in mind (Calantone and Cooper, 1981; Gaynor, 1990). While this may happen for any firm, literature has shown a strong link between new ventures' ability to carry out market research and analysis and their performance (Jayawarna et al., 2014), showing that such marketing issues are even more critical for young ventures.

Even when a new product fulfils their needs, customers may find it difficult to assess its value in comparison to competing alternatives, which is a problem because the way customers perceive the value of the product is highly instrumental in its failure or success (Cooper, 1979; Lilien and Yoon, 1989; Maidique and Zirger, 1985). This issue is especially prevalent in the case of new ventures, as their products and services are yet unknown to the customers (Jayawarna et al., 2014)). Furthermore, this problem is particularly likely to arise in the case of technology-based products (Friar, 1995), as products that are 'technology-pushed' are more likely to fail than products that are 'market--pulled' (Cooper, 1976; Gerstenfeld, 1976; Kulvik, 1977), meaning that 'technology entrepreneurs' – essentially, most startups – are particularly at risk. Marketing activities are, therefore, critical for product success (Calantone and Cooper, 1981), especially for new ventures (Phua and Jones, 2010). For the latter, while technical skills should indeed remain a priority in the early development stages, marketing resources and skills should be acquired when the product is progressing towards launch, because product (especially the first one) launch failure, unlike for more established forms, can lead to new venture's collapse (Song et al., 2010).

Indeed, successfully commercialising a new product requires creating a demand (Schilling, 2005), and this may be particularly challenging in the case of radically new products for which a market, as well as distribution/delivery channels (Brettel et al., 2011; Pellikka and Virtanen, 2009; Song et al., 2007) and manufacturing capabilities (Davis, 2002a) – which for young firms can take years to develop (Terjesen et al., 2011) – need to be created. In this respect, entrepreneurs often lack access to the complementary assets (Park and Steensma, 2012) required for successful product commercialisation (Teece, 1986), which impedes their chances of success and make their ability to create partnerships with industry incumbents particularly critical (Hsu, 2008).

Even when all these challenges have been overcome, a further source of failure for new products relates to the launch of alternative products by competition (Calantone and Cooper, 1979). Consequently, market segmentation is particularly critical as it enables to avoid direct competition with industry incumbents (Yoffie and Kwak, 2001). This is particularly important for new ventures because market segmentation enables a reconfiguration of resources, which are generally scarce in their case (Bhawe et al., 2016). Furthermore, the lead time provided by the absence of head-to-head-competition with incumbents allows entrepreneurs to improve their capabilities and learn over time, which ultimately can help their survival (Choi and Shepherd, 2004; Romanelli, 1989; Shepherd and Zacharakis, 1999).

Even when early success takes place, a further pitfall faced by entrepreneurs is that some products are difficult to scale (Steffens et al., 2009), as they were not designed with large volumes of production in mind. This forces entrepreneurs to upgrade (sometimes radically, which creates yet again a risk of failure) their products, as the first designs basically aim at discovering a product-market fit, while subsequent ones have to meet the scaling requirements (Feinleib, 2011).

A final market-related issue relates to the timing of products – and product lines – entry and exit, as poor product launch timing can lead to product failure (Bruno et al., 1992; Fields et al., 2003; 2004). In the case of new ventures, the literature has highlighted the critical role of the timing of product development – e.g. expansion, entry into new products and/or markets (Hsu, 2008).

The fourth main type of challenges faced by entrepreneurs, arguably one of the most critical ones – and perhaps one of the most specific – is the lack of financial resources (Chrisman and Leslie, 1989; Hsu, 2008; Khelil et al., 2012; Michael, 2003; Peterson et al., 1983). More than establish firms, entrepreneurs need financial resources to conduct market research (Francois, 2015), cover the cost of development of new products (Teece, 1986), acquire necessary competencies, and cover the cost of kick-starting production and distribution (Hsu, 2008). Sufficient financial resources can also help capture new markets (Auken and Neeley, 1996). In contrast, lack of financial resources increases the chances of product failure (Aarikka-Stenroos and Sandberg, 2012) and may even lead entrepreneurs to give up altogether (Blanchflower and Oswald, 1998), especially when they run out of cash before the market is ready for their product or is sufficiently developed (Feinleib, 2011).

While early product development and initial market research are indeed costly, many entrepreneurs are nonetheless still able to bootstrap (i.e. self-finance) during the early development stages. For physical products (as opposed to digital ones), however, manufacturing is generally the stage at which lack of financial resources becomes most critical, because of the high initial costs of production (Zimmerman and Zeitz, 2002). Indeed, even producing overseas in South-East Asia requires a minimum commitment in terms of production volume (Minimum Order Quantity or MOQ) and the necessity to put forward a significant amount of cash even before products start selling (Musalem and Dekker, 2005). Furthermore, this happens in a context where the actual demand for the product remains largely unknown and there are still risks that the product being manufactured is actually unfit for the market.

When entrepreneurs have exhausted their personal financial resources and can no longer fuel the growth of the company through bootstrapping, they begin to seek external funding. However, because they usually do not have sufficient collateral, getting external debts (e.g. loans) is generally difficult. At the same time, the high risk of failure makes it also challenging to attract equity investors (Busenitz and Fiet, 1996). This lack of investment in seed-stage companies is usually referred to as 'equity gap' and it is one of the major causes of failure of young businesses, which are stuck at the prototyping stage and never make it to production and sales (Rayna and Striukova, 2009).

Filling this gap requires entrepreneurs to secure investments from Business Angels and Venture Capitalists (Harrison and Mason, 2000).[3] Yet, Business Angels' investments, while useful to pursue product development, are in most cases insufficient to bridge the equity gap, which explains the reliance of entrepreneurs on Venture Capital instead (Rayna and Striukova, 2009). Thus, Venture Capital funding is certainly one of the most popular means for entrepreneurs to overcome lack of financial resources. However, Venture Capital investment is very hard to get (according to Feinleib, 2011, venture capitalists typically turn down 99% of demands) and may not even be sufficient to carry out prototype development, production and marketing (Cable and Shane, 1997), which means that entrepreneurs most likely have to go through several rounds of venture capital investment before the product is finally brought to market.

A final entrepreneurial challenge discussed in the literature relates to business models. For entrepreneurs, refining business models is critical (Felin et al., 2020; Flammini et al., 2018), as they drive entrepreneurial action and bound the implementation of organisational activities (George and Bock, 2011). Furthermore, well-designed business models can help entrepreneurs take more informed decisions (Harms et al., 2007), whereas a poor choice of business model can instead cause a young venture to fail (Morris et al., 2005). To put it plainly, entrepreneurs seldom succeed by duplicating the business model of incumbents, simply because they do not have the resources to do so. In their case, business model innovation is simply a necessity.

In any case, new venture success requires flexibility, which can be achieved, for instance by introducing new distribution channels (Hsu, 2008) or new business models (Zott and Amit, 2007). Indeed, changing directions is pivotal for entrepreneurs. However, if the course is changed too early, the idea may never be developed to its full potential, and if it is changed too late, then all the cash might get burnt. If direction is changed too often, entrepreneurs may lose the confidence of investors (Feinleib, 2011).

While not all the issues outlined in the literature are specific to entrepreneurs and new ventures – many also apply to more established businesses – they may matter more in the case of entrepreneurs and new ventures, simply because they generally have far fewer resources, whether tangible – e.g. financial resources, factories, skilled workers – or intangible – e.g. brand, reputation, intellectual property (Marion et al., 2012).

Table 1 provides a synthetic view of the entrepreneurial challenges identified in the literature. As discussed above, five broad types of challenges can be identified in the literature: New Product Development (NPD) issues, technical issues, market issues, financial issues and business model issues. This table will be used in Section 5 to investigate specifically how 3D printing technologies can help alleviate each of these five types of issues.

3. A primer on 3D printing technologies

3D printing, also often referred to as 'additive manufacturing', is a generic term used to describe various manufacturing technologies that emerged since the mid-1980s. These technologies are significantly different from other existing manufacturing technologies, in the sense that the manufactured object is built 'layer by layer' by the addition of material. In contrast, traditional manufacturing technologies generally involve the removal of material from a block of matter (e.g. sculpture, wood carving, milling—generally referred to as 'subtractive manufacturing') or the injection of a liquefied material inside a mould, in which it will solidify (e.g. injection moulding—generally referred to as "transformative manufacturing').

While in the early days, 3D printing only involved photopolymers (e.g. stereolithography) or thermoplastics (typically, using material extrusion), technological trends initiated in the early 1990s, and based on the use of laser and electron beams to sinter or melt materials (Selective Laser Sintering, Selective Laser Melting, etc.), have enabled the use of a wide range of materials (metals, ceramics, glass, plastics, food, etc.). In regard to performance, the cost of early 3D printers was exceedingly high, while the quality (i.e. resolution), build size (originally, a couple of centimetres each side), and speed were such that only but a few of the biggest R&D labs could afford to use the technology. Over time, however, costs sharply decreased and performance has notably increased. The latest estimates are that for any given performance the costs of 3D printing have been divided by 10 in the past 5 years (Wohlers, 2020).

As a matter of fact, nowadays, professional-grade desktop 3D printers can be purchased for as little as € 2,000, and there is a large choice of such printers between € 2,000 and € 3,500 (e.g. Ultimaker, Makerbot). Furthermore, open source/open hardware 3D printers, such as those provided by the RepRap community,[4] are available for less than € 2,000, typically at prices ranging € 1,000–2,000, and even less (€ 100–500) if they are purchased as self-assembly kit (e.g. Prusa).

Although these printers are comparable in terms of performance and quality to printers that were sold for € 30,000 or more just five years ago, their main drawback is that the materials they involve are restricted to plastics (including, for some of them, polymers), some ceramics, wood particles and food. They are also limited in terms of colours (usually at most two colours) and combination of materials (generally not more than two). For those aiming at multicolour 3D printed objects, metal-based objects, or objects combining various materials, the technology still remains significantly expensive. While multi-material (e.g. PolyJet) printers typically cost between € 25,000 and € 250,000 (e.g. Object500 Connex3), "metal" 3D printers cost at the very least € 150,000 (e.g. Arcam Spectra H, Metal X), with prices going up to around € 1m–€ 1.5m (e.g. Optomec LENS, SonicLayer) for the most advanced ones, which enable the largest build size.

Leaving aside printing simple plastic objects, such prices would normally keep 3D printing out of the hands of all but the largest firms.

[3] Generally, Business Angels and Venture Capitalists are complementary, as Business Angels usually invest less, but at earlier stages, whereas Venture Capitalists invest larger sums of money, but at a more mature stage.

[4] The RepRap community (http://www.reprap.org) is an open hardware community that has given birth to over 60 "official" models of 3D printers, and has been an inspiration to countless more, including most models of the "desktop 3D printer" market leaders (such as MakerBot and Ultimaker). For more details, see Bosqué (2015); West and Kuk (2016)

Table 1
Main challenges faced by entrepreneurs.

1	NPD issues	
	NPD effect on growth and survival	Nevens and Uttal (1990), Marion et al. (2012), Schoonhoven et al. (1990), Feinleib (2011), Aspelund et al. (2005), (Blundell et al., 1999), Song and Di Benedetto (2008).
	Complexity of NPD	Balachandra and Friar (1997), (Hsu (2008)).
	High failure rate of NPD	Booz and Hamilton (1982), Mansfield (1981), Cooper and De Brentani (1984), Crawford (1987), Berggren and Nacher (2001), Freeman and Soete (1997).
2	**Technical issues**	
	Importance of technical resources for NPD	Kulvik (1977), Cooper (1983), Cooper and De Brentani (1984).
	Lack of technical resources	Rothwell (1978), Song et al. (2010).
	Defective products	Hopkins and Bailey (1971), Cooper (1979), Calantone and Cooper (1979), Crawford (1987), Fields et al. (2003, 2004), Feinleib (2011), Azadegan et al. (2013).
3	**Market issues**	
	Understanding and meeting customer expectations and needs	Abetti (1986), Crawford (1987), von Hippel (1988, 2005), Rangan (1994), Schilling and Hill (1998), Berggren and Nacher (2001), Ziamou (2002), Fields et al. (2003, 2004), Bao et al. (2020), Hauser et al. (2006), Ogawa and Piller (2006), O'Hern and Rindfleisch (2010), Phua and Jones (2010).
	Poor market research and analysis	Rangan (1994), Berggren and Nacher (2001), Rubenstein et al. (1976), Cooper (1979), New and Schlacter (1979), Jolly (1997), Calantone and Cooper (1981), Gaynor (1990), Jayawarna et al. (2014).
	Uncertain product value	Cooper (1979), Maidique and Zirger (1985), Lilien and Yoon (1989), Friar (1995), Phua and Jones (2010), Song et al. (2007).
	Marketing issues (resources, activities)	Cooper (1976), Gerstenfeld (1976), Calantone and Cooper (1981), Piercy (1981), Teece (1986), Moore (1991), Christensen, 1997, Markman et al. (2008), Kulvik (1977).
	Creating demand, market and delivery channels	Davis (2002b), Woodside and Biemans (2005), Harrison and Waluszewski (2008), Hsu (2008), Pellikka and Virtanen (2009).
	Competition	Calantone and Cooper (1979), Romanelli (1989), Yoffie and Kwak (2001), Choi and Shepherd (2004), Shepherd and Zacharakis (1999).
	Market segmentation	Dwyer and Mellor (1991), Barczak (1995), Mishra et al. (1996), Calantone et al. (1997), Song and Parry (1997)
	Product entry and exit	Crawford (1987), Bruno et al. (1992), Fields et al. (2003, 2004), (Hsu (2008))
	Scaleability	Steffens et al. (2009), Feinleib (2011)
4	**Financial issues**	
	Lack of financial resources	Peterson et al. (1983), Teece (1986), Chrisman and Leslie (1989), Busenitz and Fiet (1996), Auken and Neeley (1996), Blanchflower and Oswald (1998), Michael (2003), Hsu (2008), Feinleib (2011), Aarikka-Stenroos and Sandberg (2012), Khelil et al. (2012), Francois (2015).
	Initial cost of production	Zimmerman and Zeitz (2002), Musalem and Dekker (2005).
	Equity gap	Teece (1986), Busenitz and Fiet (1996), Rayna and Striukova (2009).
	Venture Capital issues	Cable and Shane (1997), Harrison and Mason (2000), Feinleib (2011).
5	**Business model issues**	
		Morris et al. (2005), Harms et al. (2007), Hsu (2008), Zott and Amit (2007), George and Bock (2011), Feinleib (2011), Flammini et al. (2018), Felin et al. (2020).

Fortunately, services related to 3D printing have significantly expanded over time[5] to such extent that there is nowadays no need to own a 3D printer to enjoy the benefits of the technology. Printing bureaus, which enable non-owners of 3D printers to commission prints are, in fact, almost as old as the technology itself, as the first ones appeared in the early 1990s. However, it is the progress in information and communication technologies and the advent of the internet that led to a "boom" of 3D printing services, in the form of online 3D printing platforms (Rayna et al., 2015). These platforms enable users to upload a file containing a 3D model of the object they wish to manufacture, to choose the materials,[6] customise the size (as well as other options) and get a quote for the final price of the manufactured object. The largest online 3D printing platforms are, at the moment, Shapeways, Sculpteo and i.Materialise.[7]

In comparison to the other manufacturing technologies, 3D printing has critical advantages. 3D printing is much more economical than subtractive manufacturing (where up to 90% materials can be lost in the manufacturing process) (Huang et al., 2013). In comparison to transformative manufacturing (e.g. injection moulding, die casting), 3D printing displays a radically different cost structure. Indeed, while injection moulding or die casting is generally highly cost efficient for a large volume of production (typically above 5,000 units), it is highly uneconomical in the case of low volume of production (e.g. 1,000 units or fewer). The reason for that is that, leaving aside the cost of the machines, this manufacturing technique necessarily requires tooling: a mould of each part has to be created for each series. This tooling cost is far from being insignificant and even the simplest mould can cost several thousand dollars to manufacture.[8,9] Furthermore, moulds are not particularly durable and need to be replaced.

In contrast, manufacturing with a 3D printer does not require any tooling (Chen et al., 2015; Ford and Despeisse, 2016). This not only means that very small series are more likely to be economical, but also that each single unit manufactured can be modified at no cost (whereas producing units even so slightly different with injection moulding requires manufacturing a different mould).

For this reason, 3D printing enables manufacturing on demand: since there are no gains in manufacturing a large quantity of products at the same time, it becomes then possible to manufacture products when they are actually needed. This also means that each single unit produced can be customised (if needed), which makes 3D printing a key driver of mass customisation (Jiang et al., 2017; Ner and Siemsen, 2017; Thiesse et al., 2015).

Hence, the main difference between 3D printing technologies and injection moulding is that the latter is characterised by high economies of scale, whereas the former is not. Logically, this means that, as noted in Weller et al. (2015), there is a trade-off between those two different manufacturing technologies. Whereas 3D printing is more likely to be economical for small series (and that includes cases when customisation is needed), injection moulding has, in most cases, a lower cost per unit when large series are to be manufactured.

Yet, it would be a mistake to dismiss 3D printing as just a technology for small series. Indeed, 3D printing has another key advantage. Because objects are fabricated additively (layer by layer), 3D printing enables to manufacture objects with a complex shape that it would simply not have

[5] In fact, in 2014, services accounted for 51% of the revenues of the entire 3D printing industry (Wohlers, 2015)

[6] The largest platforms typically offer a choice of well above 20 materials, including metals (aluminium, brass, bronze, gold, platinum, silver, steel), plastics (clear, coloured, flexible, frosted, etc.), full-colour sandstone, porcelain, wax.

[7] Other well-know platforms, such as Thingiverse and MyMiniFactory, enable to share and download designs, but do not offer 3D printing services enabling users to obtain 3D printed objects without owning a printer.

[8] For instance, a mould enabling to manufacture a set of six ice cream plastic spoons is likely to cost over € 1,500 (Zonder and Sella, 2013).

[9] As will be discussed in the following section, 3D printing can be used to improve the efficiency of injection moulding for small series by 3D printing the moulds.

been possible to manufacture with a mould or with subtractive methods. For instance, using 3D printing, parts that would have otherwise to be manufactured separately and then assembled can be manufactured in one go, hereby saving significant assembly costs and enabling to manufacture stronger objects (Ford and Despeisse, 2016; Huang et al., 2013). Furthermore, even for objects of less complex shapes (which can be manufactured with the two other methods), the cost of manufacturing, in the case of injection moulding and subtractive manufacturing, increases with the degree of complexity: the more an object is complex, the costlier it will be to build a mould or to “sculpt” the object. In contrast, greater complexity only impacts the cost of 3D printing to a fairly minor extent, if at all (Chen et al., 2015; Huang et al., 2013).

This research aims to explore the effect of 3D printing on hurdles faced by entrepreneurs. Before proceeding, however, it is important to note that some of the effects described in the analysis section (Section 5) relate to products that can actually be manufactured with 3D printers, which is nowadays not the case for all objects. Typically, and although some progress has been made on this front over the past few years, products that contain electronics cannot be manufactured with 3D printers in their entirety, as 3D printers simply cannot manufacture as yet electronic circuit boards[10] and components (let alone, screens or batteries).

Nonetheless, the effects identified in this research can be understood as trends: the greater the proportion of an object can be manufactured directly with 3D printers, the stronger these effects are likely to be. Thus, as 3D printing technologies evolve – there are already prototypes of 3D printers able to print circuit boards,[11]- as well as electronic components –[12] the effects described below will be increasingly prevalent.

In the case of startups and SMEs, though, such effects may already exist even in the case of objects for which 3D printing is involved to a lesser extent. Indeed, for reasons of cost and sales volume, such companies tend to rely on standardised electronic components (e.g. Arduino circuit boards and components)[13] that are readily available. What is traditionally an issue are all the non-standard components—typically, in the case of electronic devices, the case/outer parts—and this is where 3D printing can come into play. Hence, in cases where 3D printing is involved to a lesser extent in the manufacturing of a product, but other parts are standardised and readily available, the effects described below are likely to be present.

A further issue that may be raised relates to product assembly. While it is possible to directly manufacture “pre-assembled” objects with moving parts with 3D printers (Calí et al., 2012)—typical examples are ball bearings, articulated figurines, whistles—not all products can be manufactured in such a manner, and even products that are entirely manufactured with 3D printers may require assembly. In such cases, the labour costs involved in assembly may lessen the effects described below, as it might then be more cost-effective to concentrate production in a particular location and over a set period of time. Yet, it should be noted that in the case of startups and SMEs, this is less likely to be the case, as, because of smaller volume of productions and lack of funding, assembly is often carried out locally by the company itself rather than outsourced (which typically comes at a later stage).[14]

Yet, even in cases when it is not possible to 3D print an entire or a significant part of an object, entrepreneurs may nonetheless benefit from using 3D printers as a part of their production process, for instance, to build prototypes or tools used as a part of the manufacturing process.

[10] Though there are methods enabling to use 3D printing to create circuit boards, the process is not easy and requires some electronics know-how

[11] https://3dprint.com/59360/dragonfly-2020/

[12] https://www.sculpteo.com/en/3d-learning-hub/applications-of-3d-printing/3d-printing-electronics/

[13] https://www.arduino.cc/

[14] See, for instance, the assembly process of the Nuimo, electronic device—now in its second batch of production—carried out by the founders of the company. https://vimeo.com/164070913 (relevant part starts at 05:06).

Table 2
Types of usage of 3D printing technologies and resulting involvement in production.

Usage	Design	Tooling	Manufacturing	Distribution
Rapid prototyping	✓			
Rapid tooling	✓	✓		
Direct manufacturing	✓	✓	✓	
Home fabrication	✓	✓	✓	✓

4. Understanding the types of usage of 3D printing

As a matter of fact, 3D printing, as a technology, can be used for a wide range of purposes and at various stages of the entrepreneurial process. Assessing the benefits that 3D printing can have for entrepreneurs therefore requires to consider what particular usage is made of the technology, and the stage of the production process it is involved in.

In regard to the first aspect, Rayna and Striukova (2016b) provide a taxonomy of 3D printing usages that categorises the many different use cases of 3D printing according to four fundamental usages:

Rapid prototyping. 3D printing is used to manufacture prototypes of parts or objects. Final products are manufactured using traditional (generally injection moulding) technologies. Resulting moulds and jigs are built using traditional methods (generally milling).

Rapid tooling. 3D printing is used to manufacture tools (jigs, but more commonly moulds) that are used as a part of a traditional mass manufacturing process.

Direct manufacturing. 3D printing is used to directly manufacture end-use products (either individual parts or complete assemblies). Manufacturing (in this case 3D printing), however, still takes place in factories.

Local/home fabrication. A further stage of evolution of direct manufacturing is when fabrication is carried out not at a global factory (or set of regional factories), but locally instead (distributed manufacturing). The ultimate stage of local manufacturing is *home fabrication*, when manufacturing is done directly at home by end users who own a 3D printer.[15]

Building on this taxonomy of 3D printing usage provided in Rayna and Striukova (2016b), it is helpful to consider that each of these particular usage affects different stages of the production process. Hence, if one considers production as consisting of four different stages – design, tooling, manufacturing, distribution – it is possible to build a mapping of 3D printing usages at the different stages of the production process. Table 2 displays this mapping and illustrates that while some usages, i.e. *rapid prototyping* and *rapid tooling* imply that 3D printing is involved at very specific stages of the production process, other usages, such as *direct manufacturing* or *(home) local fabrication* correspond to 3D printing being used in most stages or even throughout the whole production process.[16]

[15] Rayna and Striukova (2016b) define this last type of usage as “home fabrication”. However, in the context of this research, it is rather clear that reaping the benefits of 3D printing for distribution purposes does not necessarily imply that products are manufactured at each individual people’s home, but can instead be 3D printed locally, at stores, for instance, or at other people’s home. For this reason, we refer to this last type of usage as “local fabrication”.

[16] While *rapid tooling* does not strictly speaking requires prototyping to have been carried out using 3D printers, it nonetheless requires a digital 3D model, and it would be really hard to find a situation where the model in question would not have been printed beforehand as a prototype, before serving as a basis to build production tools. Same reasoning applies for *direct manufacturing*: in the unlikely event a prototype of the 3D model used for *direct manufacturing* has not been printed beforehand, the first *direct manufactured* unit is a prototype by default. Also, since *direct manufacturing* does not involve tooling, it *is* in itself *rapid tooling*. Finally, *local/home fabrication* consists in *direct manufacturing* carried out locally, and, as such, necessarily implies all the other usages.

In regard to the prevalence of each type of usage, Rayna and Striukova (2016b) point out that, while the first two types of usage—*rapid prototyping* and *rapid tooling*—are now fairly common, the other two—*direct manufacturing* and *local fabrication*—remain rather infrequent, with the former remaining chiefly a "'niche'" (though on the rise) usage in very specific industries and markets (e.g. aeronautic and aerospace, prosthetics and implants), and the latter—*local fabrication*—being even more anecdotal, considering the very low adoption of 3D printers in the general population. Recent studies (e.g. Sculpteo, 2020; Wohlers, 2020) appear to confirm that such a level of adoption of each usage still prevails nowadays.

5. The effect of 3D printing on entrepreneurship

The aim of this section is to investigate how 3D printing technologies can help overcome the challenges traditionally associated with entrepreneurship, synthesised in Table 1, i.e. *NPD issues, technical issues, market issues, financial issues, and business model issues*. However, most of these issues may arise at – or have implications for – different stages of the production process, and each particular type of usage of 3D printing – whether *rapid prototyping, rapid tooling, direct manufacturing, local fabrication* – may help alleviate each of those issues in a different manner.

Therefore, the analysis in the coming sections is organised according to Table 2. The following sections consider, in turn, the key stages of the manufacturing process – *design* (Section 5.1), *tooling* and *manufacturing* (Section 5.2),[17] *distribution* (Section 5.3), outlining in each case, when relevant,[18] the potential effect of each particular usage of 3D printing – whether *rapid prototyping, rapid tooling, direct manufacturing, local fabrication* – in relation to the issues identified in Table 1, i.e. *NPD issues, technical issues, market issues, financial issues*. Yet, those issues are not as prevalent for each stage of the production process. *NPD issues* and *technical issues* typically relate to *design and development* and will be mainly discussed in Section 5.1. Conversely, *market issues* and *financial issues* tend to be more prevalent at *production* stage (whether in relation to *tooling* or *manufacturing*) and *distribution* stage and will be more specifically addressed in Sections 5.2 and 5.3.

Finally, because it typically encompasses the whole production process – and is even broader – the last kind of issue identified in Table 1, i.e. *business models*, is addressed in a final section (Section 5.4).

5.1. Stage 1 – Design and development

As highlighted in Table 1, *design and development* issues, in particular, *new product development (NPD) issues* and *technical issues*, have been identified in the literature as one of the most critical problems faced by entrepreneurs. NPD is a *complex process* with a *high rate of failure* that affects the *growth and survival* of startups and SMEs. One of the main reasons for that is that small structures traditionally lack the resources, both tangible and intangible, that larger, well established, businesses have.

Unlike subsequent stages of the production process, i.e. manufacturing and distribution, all four usages of 3D printing identified in Section 4—*rapid prototyping, rapid tooling, direct manufacturing, local fabrication*—can be involved at development stage. Because of that, the following sections, organised by order of relevance, investigate the impact of each of these four types of usage on product development.

5.1.1. Rapid prototyping

New ventures often lack the core competencies, as well as access to the technical resources that are necessary to develop a suitable and fully functional product. One of the ways to overcome these limitations is to build as many prototypes as needed to "get it right'. However, building prototypes was until fairly recently a generally expensive, complex, lengthily and often inaccurate process.[19]

In comparison, 3D printing enables to build rapidly (in a matter of hours, instead of a matter of days, or even weeks, with traditional prototyping – hence the "*rapid prototyping*" denomination) sufficiently accurate prototypes at a significantly lower cost (Hiemenz, 2013; Zonder and Sella, 2013). As discussed in Section 3, while originally the high cost of 3D printing kept *rapid prototyping* out of the hands of startups and SMEs this is no longer the case. Not only have prices of 3D printers fallen sharply, but numerous 3D printing services enable to carry out *rapid prototyping* without even owning a printer.

With regard to *NPD issues* identified in Table 1, *rapid prototyping* enables through the building of prototypes to reduce the *complexity of NPD* and decrease the *high failure rate of NPD* and, thereby, contributes (indirectly) to *growth and survival*. Regarding *technical issues, rapid prototyping* helps avoiding *defective products*.

For instance, Pressa Bottle is a startup created in 2014 with the aim to provide a healthier and more ecological alternative to bottled sodas, by the means of a specially designed and reusable bottle, with a built-in pressing mechanism that enables to collect flavour and nutrients from fruits and vegetables, and mix them with regular water.[20] Because the pressing mechanism is embedded in the bottle and is expected to be used with a large variety of foods, it had to be carefully designed and thoroughly tested. Once the two founders had defined the original concept, they bought a 3D printer and built multiple prototypes that they thoroughly tested, involving as many people as they could in the testing process (Grunewald, 2015). Interestingly, being able to build easily prototypes with their 3D printer enabled the founders to engage in *market research*:

> Curious to see what people thought of Pressa Bottle we took it to every mall, hockey arena and college that had free Wi-Fi for our iPad survey. The results were outstanding, we were able to find an abundance of individuals using current infusing methods all experiencing the problems Pressa Bottle was made to address. We often heard "where can I buy this?" and were even asked to sell the prototype to be used! After several months of market research and showcasing the product to the public, we were able to make more revisions to Pressa Bottle based on consumer input.[21]

After six months of extensive testing, when they felt the product was mature enough, the founders took the Pressa Bottle to the crowdfunding platform Kickstarter, where it was successfully funded.[22]

However, *rapid prototyping* is not only useful for early design and concept demonstrations. For instance, Scenic,[23] a startup that successfully funded through Kickstarter the production of a universal remote,[24] also used *rapid prototyping* after their successful crowdfunding campaign to test the tolerance of the parts within a traditional mass manufacturing

[17] Tooling being itself a stage in the manufacturing process, the two were logically grouped together.

[18] Bearing in mind that, as outlined in Table 2, some key usages of 3D printing are mostly relevant at particular stages of the production process, e.g. *rapid prototyping* seldom has a significant impact beyond the design stage.

[19] e.g. making a prototype of an object out of polystyrene is unlikely to provide a fair representation of the final product, whether in terms of looks or mechanical properties.

[20] http://pressabottle.com/

[21] https://www.kickstarter.com/projects/1082826199/pressa-bottle-experience-pressed-water/description

[22] https://www.kickstarter.com/projects/1082826199/pressa-bottle-experience-pressed-water/

[23] https://www.senic.com/

[24] https://www.kickstarter.com/projects/802159142/nuimo-seamless-smart-home-interface

process.[25] Their ability to do so using a high-resolution 3D printer led to a significant decrease in the likelihood of having *defective products* at manufacturing stage.

As further noted by Christine Barlow, founder of 5 Phases (a startup that manufactures hybrid glass/plastic baby bottles),[26] *rapid prototyping* is not only useful to avoid design blunders (the first 3D printed prototype she commissioned led her to discover that the proportions of the objects were completely wrong), but also "helped when looking for a manufacturer to move into full production".[27]

In regard to *financial issues*, although entrepreneurs typically suffer from a *lack of financial resources*, the lower cost of *rapid prototyping* enables them to bootstrap the product development phase and only seek external funding at a later stage when the product has matured enough. This not only frees resources (since the entrepreneur can focus on product design instead of spending time chasing Business Angels and VCs), but also increases the likelihood of securing external funding later on (since the product presented to the investors is more mature and functional). Indeed, the ability to showcase a fully functional prototype to investors—something that was before out of reach for most startups and small businesses—can also improve the prospect of getting funded. In this respect, Allen Evans, co-founder and CTO of Avegant (a startup that has released a home theatre headset),[28] mentioned that a 3D printed prototype was highly instrumental in securing $12M from angel investors.[29] Thus, *rapid prototyping* can help closing the *equity gap* and resolve *venture capital issues*.

5.1.2. Direct manufacturing

Rapid prototyping is not the only usage of 3D printing technologies that can help alleviate entrepreneurial challenges linked to product development. *Direct manufacturing* can also be highly beneficial. Indeed, when 3D printers are used to manufacture final products, the lack of economies of scale and constant average cost means that there is very little rationale to manufacture large batches of products. As a consequence, manufacturing can be done on demand, which enables to make continuous product improvements. Thus, unlike in the case of traditional manufacturing where product development and product manufacturing are two distinct stages,[30] *direct manufacturing* enables to merge these two stages into one, as customer feedback and ideas of improvements can be immediately integrated in the product in a continuous product development process.

Entrepreneurs often have difficulties *understanding and meeting customer expectations and needs* and tend to carry out *poor market research and analysis*. This makes the ability to upgrade products continuously a critical asset, as products can be improved as entrepreneurs further their knowledge of the market and customer needs. While ICTs, in general, and social media, in particular, have proven instrumental in improving product development by enabling actual and potential customers to provide feedback at an early stage (Roberts and Piller, 2016), entrepreneurs, unlike larger firms, typically lack both the customer engagement enabling to obtain significant feedback before product launch and the resources to organise large-scale customer trials at prototyping stage. Because *direct manufacturing* enables continuous product development, it enables entrepreneurs to integrate feedback at any point and, thereby, take full advantage of the "value network" (Rayna and Striukova, 2016b) as it grows with the arrival of new customers.

Evidence of this can be found on online 3D printing platforms such as Shapeways,[31] through the feedback left by users on the products page. It is indeed quite frequent that buyers report weaknesses,[32] compatibility[33] and manufacturing issues,[34] and request changes to the product so that it better fits their needs.[35] In all these cases, while prototypes of products have been built and tested prior to product launch, *direct manufacturing* enables entrepreneurs to immediately address issues that had not been detected at prototyping stage, to change the product to better fit consumers" needs, and also to discover new market opportunities. Typical examples are those of smartphone accessories (e.g. cases, car mounts/holders) for which early adopters report design issues (e.g. the phone does not fit neatly in, the accessory hinders the use of a button or a port), reliability issues (e.g. the accessory broke after a few weeks of use), as well as wants and needs (e.g. different colour/materials, compatibility with a different smartphone or device).

Thus, by helping overcome *poor market research and analysis* and obtain a better *understanding and meeting customer expectations and needs*, the continuous development enabled by *direct manufacturing* also provides means to reduce the *high failure rate of NPD*. Furthermore, it also contributes to resolve *defective product issues*, as technical difficulties can be immediately addressed (e.g. the material used is not sturdy enough or does not meet the requirements).

However, the exploitation of the opportunities offer by the enlarged "value networks" enabled by *direct manufacturing* goes beyond user feedback and requests. Indeed, *direct manufacturing* enables firms to mobilise external resources and expertise through Open Innovation processes (Rayna et al., 2015). Open Innovation can help entrepreneurs alleviate two important issues: *complexity of NPD* and *lack of technical resources*. For entrepreneurs facing such issues, engaging in Open Innovation, through crowdsourcing for instance, can be a powerful enabler, as it permits to lower *initial costs of production*. Also, whereas entrepreneurs may *lack knowledge of the market*, the crowd, being users themselves, is generally much more knowledgeable about *customers*" expectations and needs.

The role played by *direct manufacturing* in alleviating such issues is very well illustrated by two of the current market leaders in the desktop 3D printer market: MakerBot and Ultimaker, both of which, in their early years, adopted the Open Innovation paradigm and made an extensive use of contributions provided by the members of the RepRap open source hardware community. When launching their company, both teams of entrepreneurs adopted the same "philosophy" as the RepRap open source hardware printers they used as inspiration. Sold as kits (printers could also be purchased assembled for a small additional fee), their first printers were mainly made (up to 70%) of parts that could be 3D printed, the rest being standardised parts (e.g. nuts, bolts and generic Arduino electronic cards).[36] Both companies released the blueprints of these early models, which enabled the "crowd" of users to improve the designs. It is important to note that when both companies started (2009

[25] http://formlabs.com/stories/prototyping-nuimo-smart-home-device/
[26] http://www.5phases.com/
[27] https://www.stratasysdirect.com/blog/mom-entrepreneur-begins-business-with-3d-printing/
[28] https://www.avegant.com/
[29] https://medium.com/@boonsri/how-this-3d-printed-prototype-raised-more-than-12m-in-funding-9f083d89ad9f
[30] In which case improving a product requires for existing stocks to be depleted, before a new batch can be ordered.

[31] As discussed in Section 3, Shapeways is an online 3D printing platform that operates a marketplace enabling to sell 3D printed products. Sellers simply have to upload a digital blueprint (generally an STL file produced with a CAD software) of the product onto the platform, after which products are manufactured upon purchase with 3D printers and shipped by Shapeways to the buyer (Rayna et al., 2015)
[32] e.g. http://www.shapeways.com/product/4AZMWJCFP/, http://www.shapeways.com/product/EBMDMP47L/, http://www.shapeways.com/product/JLZU9ATXH/
[33] e.g. http://www.shapeways.com/product/FPQZC4F2X/, http://www.shapeways.com/product/DJMBDM7LB/, http://www.shapeways.com/product/HFD3L8NLJ/
[34] e.g. http://www.shapeways.com/product/HYWCUYGWF/
[35] e.g. http://www.shapeways.com/product/4AZMWJCFP/, http://www.shapeways.com/product/8KWDM54G7/, http://www.shapeways.com/product/HFD3L8NLJ/, http://www.shapeways.com/product/NH2YE2JEA/
[36] http://reprap.org/wiki/About

for MakerBot, 2011 for Ultimaker), the "desktop" 3D printing was still in its infancy[37] and neither team of entrepreneurs had an experience in building machines. Their choice to rely mainly on *direct manufacturing* for their parts enabled them to overcome both *complexity of NPD* and *lack of technical resources*.

Before launching their very popular Replicator 1 (released in 2012) 3D printer, MakerBot had released two models, Cupcake (2009) and Thing-O-Matic (2010), which were largely modified and improved by the community (West and Kuk, 2016). Likewise, the customers of Ultimaker were at the origin of significant fixes and upgrades that were included in subsequent 3D printer models. In both MakerBot and Ultimaker cases, the early versions of their printers were notoriously unreliable (which exemplifies the *high failure rate of NPD* and *defective products* issues faced by entrepreneurs), and as a result the community consistently published designs of improved parts, as well as objects that provided additional features.[38] Without the ability provided by *direct manufacturing* to continuously incorporate the improvements made by users, it is highly unlikely that either firm would have been as successful (for one, they would both have been left with large stocks of poorly performing products they would be unable to sell, and would have most likely gone bankrupt).

A further interest of these two cases is that they relate to products that could only partially (albeit to a large extent) be 3D printed, which demonstrates that the benefits brought about by 3D printing to entrepreneurs are not restricted to products that can be manufactured entirely with 3D printers. The combination of 3D printed parts with standardised parts enables entrepreneurs to benefit from *direct manufacturing* even for fairly complex products. It is also to be noted that, as years went by, subsequent models of both manufacturers included fewer and fewer *direct manufactured* and standardised parts, using instead mass manufactured specialised parts. As both companies gained in expertise and their products in maturity, the benefits of direct manufacturing were no longer as prevalent and were offset by the large economies of scale (and resulting lower manufacturing costs) enabled by mass manufacturing.

Besides overcoming *NPD and technical issues*, the use of *direct manufacturing* at early commercialisation stage can also help overcome *market issues* by enabling mass customisation (Salvador et al., 2009). As noted in Section 2, market-related issues faced by entrepreneurs relate, amongst other things, to the difficulty to *create demand* and to carry out *market segmentation*. The ability to mass customise, through the use of *direct manufacturing*, not only helps create value for customers (hereby potentially fostering demand) but also enables to finely *segment the market*. In fact, as discussed in Petrick and Simpson (2013), *direct manufacturing* enables market segments of size one, where each customer becomes a particular segment. Without going as far, it is clear that the ability to customise products at no extra manufacturing cost eases segmentation and, as a result, potentially increases demand.

Furthermore, mass customisation can help alleviate other *market issues*. Indeed, *understanding and meeting customers expectation and needs* is much easier if customers are able to directly show what they want. If customers are able to customise, this may also reduce their perceived *uncertainty about product value*. In an environment where entrepreneurs *lack financial resources*, mass customisation can be a good substitute for (generally) *poor market research and analysis*.

While mass customisation can, of course, take place through direct interactions with customers, online platforms such as Digital Forming[39] provide entrepreneurs with a visual interface that enables clients to extensively customise their products (within limits provided by the designer so that the product still operates as expected). When customers are satisfied with the changes they have made, the product is 3D printed and shipped to them. For the companies using this platform, this enables to segment the market at a fairly low cost, and the analysis of the changes made by customers provides highly valuable insights into their needs.

5.1.3. Local/home fabrication

Home fabrication entails end users (generally consumers) being able to manufacture products themselves with the use of 3D printers (Rayna and Striukova, 2016b), however, as noted above, the ability to 3D print at home is not necessary for 3D printing to be involved in close distribution of products, as long as 3D printing capabilities are available *locally* (whether in the building, in nearby shops, at a neighbour, etc.). In either case, *local/home fabrication* relates to a form of *direct manufacturing* (albeit distributed) and, thus, embeds all the benefits of the use of *direct manufacturing* in relation to the design and development stage described in Section 5.1.2. Yet, in relation to design and development, the use of *home and local fabrication* has further advantages. As users are able to print and test their suggestions of improvements, these are not merely theoretical, but actual (and tested) solutions to the problem (or need) they contribute to. The ability of users to build and test improved parts, whether at home with their own printer, at work with their company's printer, or at a local fab lab or makerspace, was highly instrumental in the product development of the first MakerBot and Ultimaker printers discussed in the previous section, and has enabled these companies to considerably cut their development costs.

Local fabrication at development stage can be particularly beneficial when potential customers are located far away (and are not clustered), which was the case of MakerBot and Ultimaker, whose potential customers were scattered across the globe. In other cases, however, the benefits of doing so may not be that obvious. For instance, while the founders of Pressa Bottle could have shared the digital blueprint of the prototype online and gather feedback from all around the world, showing their prototypes in the shopping malls around them, where they could meet a number of their target customers, was sufficient.

In this respect, one of the key issues of using *local fabrication* at development stage relates to Intellectual Property, as anyone who has access to the prototype could decide to keep the improvements they have made to themselves and commercialise the product instead. This is why *local fabrication* used at development phase fits particularly well "open" models, such as those used by MakerBot (until 2012) and Ultimaker.

However, it must be noted that nowadays, and most likely in the years to come, the vast majority of 3D printers that can be found in a home or in an office are only able to produce rather crude objects. That may be enough to test if the prototype is functional and ergonomic, but may not be sufficient to showcase its design, for instance. On the one hand, this may help alleviate some of the IP issues mentioned above (users may test the prototypes, but still be willing to buy the final, higher quality, product), on the other hand, this potentially hinders feedback and suggestions related to design.[40]

A last impact of *local fabrication* in relation to design and development stage is that having a 3D printer at hand enables end users and consumers to become entrepreneurs. For instance, the founders of Pressa Bottles started their business at home, using a desktop printer they

[37] At the time, the available body of knowledge mainly related to the construction of large industrial printers. Building printers compact enough to fit on a desk and costing a tenth of the price came with an entirely different set of constraints.

[38] For instance, the Thingiverse platform lists over 500 original parts and improvements contributed to the Cupcake printer and over 800 for the Thing-O-Matic printer. http://www.thingiverse.com/search/page:2?sort=relevant&q=cupcake&type=things, http://www.thingiverse.com/search/page:1?sort=relevant&q=thing-o-matic&type=things. Likewise, over 1300 contributions were made to the Ultimaker 1 and 2 printers. https://www.thingiverse.com/tag:ultimaker/

[39] http://www.digitalforming.com

[40] These can, however, be obtained through other means, e.g. realistic 3D renderings of the object hosted online.

bought to build the first prototypes.

5.1.4. Rapid tooling

As *rapid tooling* generally happens *after* the design stage and *ahead* of the manufacturing process, one could think that such usage of 3D printing does not provide meaningful benefits in relation to design and development. Yet *rapid tooling* can play a role similar (albeit to a different extent) to *rapid prototyping* and *direct manufacturing* discussed in the Sections 5.1.1 and 5.1.2.

As discussed in Section 4, *rapid tooling* consists in using 3D printers to build tools, generally moulds and casts used for injection moulding. As such, it is more generally used as a part of a manufacturing process. Yet, there are cases when *rapid tooling* can be beneficial during design and development stage. This typically happens when the materials used for the prototype cannot be 3D printed (e.g. wood)[41] or when it is not economical to do so (e.g. gold). In such cases, a mould can be 3D printed to produce the prototype by injection moulding. Thus, *rapid tooling* is a substitute to *rapid prototyping* when the latter is not (economically) feasible. While not as effective as *rapid prototyping* (it is a, longer, two-stage process that requires heavier equipment, since it involves injection moulding), *rapid tooling* shares, albeit to a lesser extent, the benefits of *rapid prototyping* at design and development stage described in Section 5.1.1.

Furthermore, because manufacturing moulds with 3D printers is significantly cheaper and faster than with traditional methods (Zonder and Sella, 2013), *rapid tooling* makes it economical to manufacture smaller series and offers far shorter lead time. Consequently, *rapid prototyping* used at development stage offers some of the benefits provided by *direct manufacturing* and discussed in Section 5.1.2. Smaller batch of products and lower cost of tooling mean that products can be updated more frequently based on user input. Likewise, *rapid tooling* makes some form of customisation possible and enables greater *market segmentation* than traditional manufacturing methods.

5.2. Stages 2 & 3 – Production: Tooling and manufacturing

Out of the four key usages of 3D printing identified in Section 4, only two—*rapid tooling* and *direct manufacturing*—are directly relevant at the manufacturing stage and will be addressed in this section. *Rapid prototyping* is (by definition) only used at design and development phase (Section 5.1), although, of course, prototyping has impact on both tooling and manufacturing – for instance, once a “design” prototype has been approved, a “manufacturing” prototype is often built to ensure that the related object can be reliably manufactured. The fourth type of usage, *local fabrication*, of course, relates to manufacturing, since it means manufacturing objects, albeit locally. However, it is basically *direct manufacturing*, but carried out in a decentralised local, manner. For this reason, the “manufacturing aspects” of *local fabrication* are discussed in this section under the “umbrella” of *direct manufacturing*, while the more specific aspects of distribution will be discussed in the following section (Section 5.3).

Therefore, because the current section only addresses two of the four key usages, and also because the two remaining ones – *rapid tooling* and *direct manufacturing* – not only share (albeit to a different extent) common benefits in relation to manufacturing issues, but are also often used in combination (e.g. *direct manufacturing* at first and then *rapid tooling* for larger volumes of production), the current section is not organised by types of usages. Instead, it is organised according to the main types of issues affecting the manufacturing stage (as presented in Table 1) and that 3D printing may help alleviate: *financial issues, scaleability*, and *market issues*.

5.2.1. Overcoming financial issues

Financial issues are certainly amongst those most often associated with manufacturing. Indeed, traditional manufacturing entails significant upfront costs. Aside tooling, which can already be expensive,[42] entrepreneurs willing to commercialise a product need to commit to purchasing of a sufficiently large number of units from the manufacturer. This minimum order quantity (MOQ) typically ranges from a several hundred units for garments to tens of thousands units in the case of objects and electronics (Musalem and Dekker, 2005; Zhou et al., 2007). Furthermore, because nowadays most products are manufactured in South-East Asia, significant shipping costs are incurred by entrepreneurs at manufacturing stage.

Low volumes of production clearly make the matter worse. A large company would order hundreds of thousands of units at a time, and consequently secure large volume discounts on manufacturing and transportation, and, furthermore, would be able to spread the fixed cost (e.g. tooling) across many more units. In contrast, startups and SMEs are often in a situation when they order small batches of products and, as a result, face a significantly higher average cost. Thus, entrepreneurs typically face higher *initial cost of production*.

Lead time is another issue. Products manufactured in South-East Asia have a typical manufacturing lead time of over a month, and that does not even account for tooling lead time, which can also take several weeks (Zonder and Sella, 2013). This means that entrepreneurs not only need to invest a significant amount of money upfront, but also have to wait for weeks, sometimes months, before they can begin selling even a single unit of their product.

Thus, while bootstrapping may be fairly common at development stage, it is more rarely the case at manufacturing stage. In fact, upfront costs related to manufacturing are typically where the entrepreneurs' *lack of financial resources*, identified in the literature, is the most prevalent. Because it is far more difficult to bootstrap manufacturing, this is generally at this stage that entrepreneurs will seek external funding whether through loans or *venture capital* (Zider, 1998).

In fact, the traditional commercialisation model is characterised by *negative cash-flow*. In order to commercialise a product, entrepreneurs must first borrow money (from a bank, investors, etc.). With the money they have borrowed, they pay for the manufacturing of their products, which they then try to sell in order to reimburse the money they have borrowed in the first place (hopefully, recovering enough money to make a living as well).

It is easy to see what might go wrong (and actually often does) with this model. Indeed, the quantity of product manufactured is based on an estimated demand, which, because of *poor market research and analysis, uncertain product value, marketing issues* or poor *market segmentation* may simply not actually exist (or, at least, not to the extent projected). Especially in the case of a new venture, *defective products* may arise (if the product was badly designed, the whole production batch may be affected). Furthermore, the manufacturing lead time creates additional risk. Between the time the product is ordered and its actual delivery, market changes may occur that make the product less relevant (e.g. weather change, Apple has changed the size of its smartphones again).

Bearing all that in mind, it is not hard to understand why, considering such a risky prospect, banks and investors may be reluctant to fund such a venture. This is indeed typically when *equity gap* and *venture capital issues* are more likely to arise (Rayna and Striukova, 2009).

To understand how 3D printing technologies may alleviate financial issues at production stages, it is, again, important to consider how they are used. In this respect, *rapid tooling* has a significant, but moderate impact. 3D printing moulds instead of milling them typically halves the cost of tooling and reduces tooling lead time to a matter of hours, instead of weeks (Zonder and Sella, 2013).[43] As noted above, *rapid tooling* also

[41] Although composite materials embedding wood particles are available.

[42] Moulds enabling to manufacture even the simplest objects, such as plastic spoons or threaded caps, can cost thousands of euros (Zonder and Sella, 2013)

[43] Tooling lead time can be further reduced, because the digital blueprint of the mould can be sent electronically to the production site and manufactured there with a 3D printer, instead of having to ship the mould itself.

enables finer *market segmentation* and makes upgrades more economical, which can help resolve issues related to *defective products* and *poor market research and analysis*. Yet, the impact of *rapid tooling* is, by nature, limited because traditional manufacturing techniques (typically, injection moulding) still have to be involved and, and as a result, a significant investment is likely to be required to start manufacturing.

In contrast, *direct manufacturing* has a more transformative impact. Using 3D printing to manufacture products means that no significant investment is required: *direct manufacturing* does not entail either tooling costs or minimum order commitments, and the manufacturing cost per unit remains constant over the whole production range. As discussed in Section 3, owning a 3D printer is not even required, since online platforms, local printing bureaus, Fab Labs and makerspaces enable entrepreneurs to use 3D printing for manufacturing without even owning a printer.

Furthermore, as highlighted in Section 5.1.2, the constant cost per unit associated with *direct manufacturing* and its comparatively short lead time enable entrepreneurs to manufacture on demand. While manufacturing on demand already has critical advantages in regard to product development (discussed in Section 5.1.2), it also has the potential to completely reverse the commercialisation and manufacturing model, as it enables *positive cash-flows*.

Indeed, whether outsourced (through a 3D printing platform or a local bureau) or carried out directly by entrepreneurs equipped with 3D printers, on-demand manufacturing means that customers pay first, and then the product is manufactured. Thus, sales take place *before* manufacturing, which is the exact opposite of the traditional model where manufacturing takes place first and then customers (hopefully) purchase the product.

Positive cash-flows, associated with the (virtual) lack of upfront costs associated with *direct manufacturing* enables to considerably alleviate the issues related to *lack of financial resources* faced by entrepreneurs and makes it far more likely that they will be able to bootstrap manufacturing using their own financial resources. As a consequence, obtaining external funding becomes far less critical, which tends to resolve both the *equity gap* and the *Venture Capital issues*.

One only needs to take a look at the leading online 3D printing platforms to see how impactful *direct manufacturing* potentially is. On Shapeways alone, over 420,000 products—accessories, jewellery, games, figurines, kitchenware, home equipment, spare parts—are offered for sale, at prices ranging from just $1 to close to $3,000. For entrepreneurs, starting to manufacture through such a platform is a rather straightforward (and costless) process. They simply need to upload a digital file (generated with a CAD software) enabling to 3D print the product. The platform then supplies a quote of the manufacturing cost (shipping costs are covered by customers), to which entrepreneurs add a markup of their choice. The price of the item is then listed on a page hosted by the platform, on which entrepreneurs can add photos and information about the product. When a purchase is made, the platform handles the payment, manufactures and ships the product to the customer, and pays the markup to the entrepreneur. Neither of the three largest platforms (i.Materialise, Sculpteo and Shapeways) charge upfront costs of any kind. For instance, Shapeways advertises on its related help page:

> Be profitable after your very first sale. No upfront investment, no need to carry inventory. You design, set markup, and share your products. We handle the rest.[44]

Some entrepreneurs prefer nonetheless to handle manufacturing themselves. The cost of a 3D printer, while significant (between € 300 and € 3,500 for plastic, as noted in Section 3) may be rapidly offset (owning a 3D printing also helps speeding up the development process). For instance, Chris Milnes, who spotted a market opportunity for a smartphone accessory that could be used with the Square smartphone payment system,[45] discovered after building a prototype that it would cost him between $4,500 and $6,000 just to get the mould required to have this (small) widget manufactured by injection moulding.[46] Having the product manufactured in China would also lead to a $0.30 unit cost and require several thousands of units to be ordered upfront.[47] Instead, Chris Milnes realised that he could manufacture the item himself by purchasing a $2,200 3D printer, with a $0.05 unit cost, and that he could manufacture up to 700 units per week with just one printer. Chris set up a simple website to sell his product[48] and used PayPal to process the payments. Three months after launching his product, Chris Milnes had manufactured and sold over 9,000 units at a price of $8 each,[49] and, in light of the increased demand for the product, purchased a second 3D printer.[50]

Hence, the use of 3D printing at production stages, in particular when *direct manufacturing* is involved,[51] enables to help overcome most of the *financial issues* identified in the literature (Section 2) and displayed in Table 1. Indeed, by sharply decreasing the *initial cost of production* – on-demand manufacturing leads to an actually progressive cost of production – *direct manufacturing* makes *lack of financial resources* much less significant at this stage, since little resources are required to begin manufacturing and selling. As noted above, this alone would reduce the need for external investment at production stages, making *venture capital issues* and the resulting *equity gap* much less pregnant issues. But as described above, the benefits of *direct manufacturing* can go beyond simply reducing upfront costs by making them progressive, as it enables 'positive cash-flow' models that may free entrepreneurs of (significant) financial constraints related to production stages. And while external funding may still be required at a later stage to ramp up production, the benefits in terms of *scaleability*, discussed in the following section, may help overcome the resulting *venture capital issues* (if there are any remaining).

5.2.2. Overcoming market issues

Indeed, besides helping overcome *financial issues*, 3D printing also has key benefits in relation to resolving *market issues* faced by entrepreneurs. Amongst the *market issues* identified in Section 2, *scaleability* is certainly a traditional pitfall for entrepreneurs. The lack of scaleability of traditional manufacturing not only impedes *market entry* (difficulties to scale down—getting rid of existing stocks—if a product does not sell as well as expected), but also makes startups and SMEs fail because they are 'too successful' (difficulties to scale up—acquire new stocks—if a product sells better than expected).

Because *direct manufacturing* enables to manufacture on demand with a short lead time,[52] it allows to escape this 'stock logic'. Scaling down is never an issue, since only what is actually needed is manufactured. Scaling up can be done (comparatively) smoothly and in a flexible manner, for instance, like Chris Milnes did, by purchasing (or leasing) additional 3D printers. Another option is to outsource production to an

[44] https://www.shapeways.com/sell/open-a-shop

[45] http://squareup.com/

[46] Source: interviews of Chris Milnes, http://bcove.me/bvcuojom, https://youtu.be/y1W5gCMpCVU.

[47] In the interviews Chris Milnes also mentions his concerns about not being able to improve the product if it were mass-produced.

[48] http://www.squarehelper.com

[49] Yielding a net profit of $69,350 in just three months.

[50] https://3dprintingindustry.com/news/making-money-from-3d-printing-square-helper-7648/, http://bcove.me/bvcuojom

[51] As noted, some of the benefits may also arise through *rapid tooling*, albeit to a much lower extent.

[52] While 3D printing is not intrinsically a particularly fast process—manufacturing one single large object can take several hours—it is nevertheless significantly faster than regular manufacturing, which requires weeks just to be set up.

online 3D printing platform or a local 3D printing bureau, who generally have significantly larger *direct manufacturing* capacity. Unlike "traditional" outsourcing, there is no set-up cost and starting production simply requires sending a digital blueprint of the object. A further source of flexibility in scaleability lies in the fact that different sources of manufacturing can be combined. For instance, a small business that owns a couple of 3D printers can complement its production during peak demand periods by using platforms or bureaus and does not face need to invest in additional printers unless the extra demand becomes regular.

On a side note a further *market* benefit, which is also a *financial* benefit of owning 3D printers relates to *scaling* down (whether temporarily or more permanently). Because 3D printers can produce any object – within the printing capabilities of a particular printer – spare capacity can be rented (at little to no cost to the owner) to other companies facing manufacturing needs, hereby securing a return on an investment that would otherwise not have been possible.

Yet, as mentioned in Section 3, *direct manufacturing* is only economical for (relatively) small volumes of production. Unless products are mass-customised or have a complex design that is such that it cannot be manufactured through traditional means (i.e. a shape or structure that can neither be milled nor moulded), there is always a volume of production above which mass manufacturing is more economical.[53]. Nonetheless, even in this case, 3D printing enables scaling up, as the digital blueprints used for *direct manufacturing* can be used to build the mould (*rapid tooling*) needed for injection moulding. If, for any reason, the resulting upfront costs still create a funding gap, it is far more likely that investors (or banks) will be willing to invest in a product that has already sold thousands of units, than in a product that has not been commercialised yet.

A typical example of the benefits of 3D printing in manufacturing is provided by the startup Max'is Creation.[54] The arts and craft school project of an 8-year-old named Max—a hand-built clay chocolate mug featuring a basket hoop enabling to throw marshmallows in it—that rapidly ended up being copied by many of his classmates, became the basis of an entrepreneurial venture. The first prototypes, designed with the help of a local 3D printing bureau, enabled not only to test the most adequate dimensions for the hoop and mug, but also, upon suggestion of early testers, to prototype mugs related to other sports (baseball, football, American football, hockey).[55] The first units were directly manufactured with 3D printers, which enabled to offer them to local retailers and also to further improve the product as early customer feedback came. As the volume of sales increased, *direct manufacturing* was no longer an option (retailers needed stock). Max'is Creation used *rapid tooling* to build moulds in order to switch to mass manufacturing through injection moulding. As the product was in high demand (for instance, 18,000 mugs were sold during the winter holiday 2014, three times more in 2015), production had to be ramped up quite significantly, which created a potential funding gap. Interestingly, instead of seeking Venture Capital investment, Max's parents crowdfunded manufacturing through the Indiegogo platform.[56]

Finally, 3D printing technologies help alleviate three further *market issues* identified in Table 1. The high scaleability of manufacturing enabled by 3D printing contributes to easing *product entry and exit issues*. Since *direct manufacturing* can begin at a very short notice, this decreases the risk of launching a product at the wrong time, because large stocks of products are less likely to be needed. Reduced need for stocks also eases product exit, should it be needed.

In regard to *competition*, 3D printing provides a greater adaptability, through scaleability and continuous development. However, it is important to note that this does not necessarily provide a competitive advantage, especially when competing with mature and well-established products—most likely mass manufactured—and whose average cost of production is likely to be comparatively very low. In such a case, competitive advantage is more likely to arise from differentiation, mass customisation in particular, and integration of the end users and customers in the *value network* of the company (Rayna and Striukova, 2016b).

Finally, *marketing issues*, whether related to *resources* or *activities*, have been identified in Table 1 as being a key entrepreneurial challenge. In this respect, it can be noted that *direct manufacturing* can reduce the need for large-scale and costly marketing activities, which are generally needed because large quantities of products need to be sold rapidly to avoid storage costs and recover the money invested in manufacturing. Instead, *direct manufacturing* enables a more progressive sale growth that can be fuelled by word-of-mouth and targeted Social Media marketing. As manufacturing is made on demand, there is no hurry to sell.

5.3. Stage 4 – Distribution

This section aims to investigate the impact of 3D printing for entrepreneurs on issues related to distribution of their products. Indeed, 3D printing is not "just" a prototyping and manufacturing technology, but can also be used to distribute products, by manufacturing them closer to the customers, hereby reducing the needs for transportation.

Indeed, while *direct manufacturing* can (and often does) take place at centralised factories, in many cases, because of the lack of significant economies of scales associated with 3D printing as a manufacturing technology (as noted earlier, the cost per unit remains constant), concentrating manufacturing with 3D printing in a particular location (or a small set of locations) – or, for the matter, time – is not particularly economical. As a result, 3D printing technologies are enablers of distributed manufacturing (Ford and Despeisse, 2016; Ford et al., 2016). In lieu of being manufactured in large quantity at a handful of worldwide factories, products are manufactured directly with 3D printers located in the customer's neighbourhood (Rauch et al., 2016). Doing so means that manufacturing becomes part of the distribution process and logistical and opportunity costs are reduced (Rogers et al., 2016). As noted in Rayna and Striukova (2016b) and discussed in Section 4, 3D printing technologies are, therefore, enablers of *local fabrication*, that can even extend to the consumers' own homes, once they are equipped with a 3D printer. This is of significant importance for entrepreneurs, as – as noted in Table 1 – product distribution is also a source of challenges for them, in particular in relation to *market issues* and *financial issues*.

5.3.1. Overcoming market issues

One of the key effects of 3D printing used for *local fabrication* is that it provides entrepreneurs with access to new *delivery channels* for their products. Such channels are either operated by third parties (e.g. local 3D printing bureaus, 3D printing platforms) or by the entrepreneurs themselves.

While *local fabrication* can be handled directly by entrepreneurs, who can contract local 3D printing bureaus wherever they see fit, online 3D printing platforms, such as Sculpteo, Shapeways, i.Materialise or Kraftwürx, also provide a transparent *local manufacturing* service, as they own (or outsource) 3D printing facilities in many countries. Consequently, an entrepreneur making use of these platforms to manufacture its products will automatically benefit (in terms of lead time and cost of delivery) from the fact that they operate 3D printers close to their customers, and even in countries or regions of the world where they do not operate.

However, some entrepreneurs prefer to take matters in their own

[53] It is generally admitted that, other considerations left aside, injection moulding is more economical than *direct manufacturing* for any volume above a few hundreds (occasionally a few thousands) units (Berman, 2012; Franchetti and Kress, 2017; Gebler et al., 2014)

[54] http://maxiscreations.com/

[55] http://www.3dsystems.com/blog/2015/10/3d-printing-turns-creative-young-mind-entrepreneur

[56] https://www.indiegogo.com/projects/max-is-creations-mug-with-a-hoop-tm/

hands, because they prefer to retain more control, require an even shorter lead time, or because their product is too complex (e.g. involves electronics) to be manufactured by such platform. Fairphone's[57] case relates to the former. Fairphone commercialises "ethical" smartphones, which offer a modular design that enables a high durability (since parts can be upgraded or replaced if they fail) and recyclability. Fairphone also uses "fair materials" and promotes "good working conditions" in the factories where the smartphones (which, obviously, cannot be 3D printed) are manufactured.[58] In addition to direct sales online, Fairphone was able to sign distribution deals for its smartphones with major telecommunication operators (e.g. T-Mobile, KPN, Swisscom, Post-Telecom). However, one of the issues they were facing was the lack of *delivery channels* for accessories (e.g. cases, stands, car mounts) for their phones – accessories whose availability can be critical in the adoption of the product by consumers.

Conscious of the carbon footprint of the distribution of their products and aware of the advantages provided by 3D printing, Fairphone decided to team up with 3DHubs, one of the largest manufacturing crowdsourcing (or rather 'crowdmaking') platform (Rayna et al., 2015),[59] which enables owners of 3D printers—generally end users—to offer 3D printing services to others. Hence, accessories for the Fairphone can be ordered directly online and are manufactured by the 3DHub user located the closest to the customer.[60] [61] In large cities, such as New York City, London or Los Angeles, where over 300 local "printers" offer their services, chances are that the accessory will be manufactured and ready to pick up in the customer's vicinity. Interestingly, Fairphone also offers to those customers who own a 3D printer to directly manufacture accessories themselves, which demonstrates the potential of *local fabrication* as an enabler of *delivery channels*.

Yet, of course, one of the key issues associated with *local fabrication* relates to Intellectual Property, as this necessarily implies sending the 3D model files required to print the object to customers (in the case of *home fabrication*) or to local third parties. Those files can be shared just as easily as music files, movies, etc., and once they have been sent, there is little way to control what will become of them. Consequently, there have been concerns that the widespread piracy phenomenon that has been witnessed in other digital industries could, through 3D printing, reach the realm of physical objects (Petrick et al., 2014).

While thoughts have been given to circumventing copying and sharing by means of technological solutions (such as DRM—Digital Rights Management), these have shown in the past largely ineffective (Rayna and Striukova, 2008). As a result, while the low proportion of households equipped with a 3D printer is also certainly a key factor, there have been very few examples so far of digital sales of objects to consumers. One of the exceptions is the platform 3DShook, aiming to sell 3D models of objects that can be printed by customers at home.[62] In order to alleviate piracy issues by disincentivising it (just like Spotify and Netflix did), 3DShook uses a subscription-based model that enables users to download and 3D print objects as many times as they want for a flat fee.

The benefits of using 3D printing as a means to distribute products, however, does not only relate to small objects that can be (almost) entirely 3D printed, and in the past few years, entrepreneurs have engaged in far more ambitious ventures. Two of them, Local Motors[63] and Divergent3D[64] ambition—no less—to revolutionise the car manufacturing industry. Both startups offer fully functional cars that are 3D printed to a significant extent, and can hereby be fully customised to fulfil specific customer needs (e.g. purpose, environment, disabilities). Fully aware of both the high efficiency of production lines of traditional car manufacturers and the significantly high investment required to manufacture and distribute cars, both teams of entrepreneurs have decided instead to rely on "micro-factories", i.e. small-size manufacturing facilities located close to customers that enable distribution as well as manufacturing.[65] [66]

Besides enabling entrepreneurs to set up and find *delivery channels, local fabrication* also has a positive impact on *product entry and exit*, as it enables entrepreneurs to rapidly move (or cease operations) in a particular country. For instance, back in 2014, Kobrin,[67] an Italian startup started to manufacture and sell 3D printed eyewear. However, they rapidly discovered that there was "no internal demand" in Italy and, as a result, they had to "re-[localise] production where demand and opportunities are highest".[68] Teaming up with a local incubator in Brazil, they were able to rapidly shift production there (while retaining manufacturing capabilities in Europe through other partnerships). Thus, the use of *local fabrication* enabled Kobrin to '*exit*' a market that was not promising as expected and rapidly '*enter*' a more dynamic one.

These examples are indicative that, in addition to being instrumental in solving *distribution channel issues, local fabrication* can be instrumental in helping resolve many other *market issues* faced by entrepreneurs, such as *product entry and exit, market segmentation* – in particular when it relates to geographical segmentation. As highlighted in the examples above, there are indications that making use of *local fabrication* can help alleviate the consequences of poor *understanding and meeting customer expectations and needs, poor market research and analysis, uncertain value product* (as fabricating locally, even through intermediaries, enables to have a better understanding of the local customers and markets).

Another key benefit of *local fabrication* in relation to *market issues* relates to *scaleability*. Generally, 'upward' scaleability relates to increasing volumes of productions to enable a greater supply for the same geographical markets or for additional geographical markets. When *local fabrication* is not involved, this generally means the same thing: ramping up production at one global factory or at a small set of regional factories. When 3D printing is involved, *local fabrication* offers two drivers of 'upward' scaleability. In relation to a particular geographical market, *local fabrication* enables to make use of various local 3D printing production capabilities (which, despite a relatively low consumer adoption, are available to a significant extent in medium and large cities worldwide)[69]. However, the examples above indicate that *local fabrication* can become a key driver of geographical 'upward' scaleability, enabling entrepreneurs to ramp up production to serve new markets at different locations.

Nevertheless, as discussed before 'upward' scaleability is not the only critical issue faced by entrepreneurs, and their ability to 'downsize' is often just as important. Because it enables 'on-demand' local production, *local fabrication* enables just that. As illustrated by the Kobrin case in particular, scaling down because the market at a particular location 'is just not there' (yet) is not an issue, as no (significant) investment has been made. If the market is not there, we just move somewhere else (or

[57] http://www.fairphone.com/
[58] https://www.fairphone.com/en/our-goals/
[59] As of Q1 2017, 3DHubs enables to manufacture using close to 7000 3D printers located in over 150 countries. https://www.3dhubs.com/trends/q1-2017
[60] https://www.3dhubs.com/fairphone
[61] https://3dprintingindustry.com/news/63799-63799/
[62] http://www.3dshook.com/
[63] http://www.localmotors.com/
[64] http://www.divergent3d.com/
[65] https://localmotors.com/microfactories/
[66] https://3dprintingindustry.com/news/gorgeous-modular-supercar-made-possible-by-3d-printing-51957/
[67] http://kobrin.co/
[68] http://3dprintingindustry.com/news/3d-printed-glasses-start-kobrin-unites-3-continents-localized-manufacturing-32416/
[69] As demand increases, more 3D printing providers are contracted, and one could even imagine a company facing a large demand involving consumers and end users through 'crowdmaking' platforms such as 3D Hubs)

improve the product based on local feedback and try again).

Finally, it is important to note that *local fabrication* enables to overcome some *market issues* that might not have been as successfully resolved if *direct manufacturing* had been used, but in a more centralised manner (i.e. production at one 'global' or set or large-scale 3D printing factories, instead of locally), as the latter may still imply that batches of products are manufactured ahead and that stocks of product exist.

5.3.2. Overcoming financial issues

Besides outlining the important role that *local fabrication* can have in relation to *market issues*, this last example also highlights the impact that this use of 3D printing can have in relation to *financial issues*. As discussed in Section 2, *lack of financial resources* is a traditional pitfall for entrepreneurs. In the case of Kobrin, the failed Italian market entry at such an early stage in the venture could simply have been fatal for the company, who would have had to put forward a significant amount of cash to enter this market (set up a local bureau, rent warehouses, manufacture and stock the product, set up contracts with local distributors, etc.), most of which would not have been recoverable if the demand had been just not there. Likewise, 'pivoting' to a new market – in this case, located on the other side of the planet – would also have required significant *financial resources* that entrepreneurs would be unlikely to have at their disposal (especially after a first 'debacle').

Instead, the case of Kobrin highlights that *local fabrication* can be instrumental for entrepreneurs, as it enables to enter markets at a very low cost, with little (if any) commitment, and, overall, a need for relatively little *financial resources* and, hence, a rather low financial risk entailed.

Another advantage of *local fabrication* in relation to the *lack of financial resources* faced by entrepreneurs highlighted by the Kobrin case relates to taxation. Indeed, a traditional hurdle for entrepreneurs 'strapped for cash' when venturing abroad relates to the sometimes very high import duties they have to face. And while larger companies may be able to bypass such financial issues by setting up local plants and factories, such device has been traditionally out of the hand of most entrepreneurs.

In the case of Kobrin, *local fabrication* through 3D printing enabled them, though as 'small' as they were to do just that. By manufacturing locally in Brazil with 3D printers, they were able to bypass the 60% import tariffs they would have otherwise faced if they had imported their product. Considering the strong financial constraints faced by entrepreneurs, especially at a time when, worldwide, trade barriers between countries are on the rise, this is certainly another important advantage provided by *local fabrication*.

A final note on the benefits of *local fabrication* in relation to *overcoming financial issues* is that, traditionally, as discussed above, opening a new geographical market is a major hurdle, that requires a large investment (in stocks, logistics, distribution capabilities, etc.), i.e. *initial cost of production*, for which entrepreneurs typically *lack financial resources*. This is usually one of the key reasons for which they will seek external funds – bank loans, but more generally *venture capital*. Because *local fabrication* makes it such that such large investment is no longer required when entering new geographical markets, it helps bridge the *equity gap* issue that many entrepreneurs face.

5.4. Business models

As discussed in Section 2, *business models issues* have been rightly identified in the literature as one of the most critical problems faced by entrepreneurs, as they more often than not are required to find innovative business models to be able to compete with well-established incumbents, simply because (as discussed in the previous section) they are likely to be at cost disadvantage. In this respect, the great potential flexibility, liberty, and inventiveness that 3D printing provides can be expected to be highly beneficial for entrepreneurs, in particular in relation to the relatively low 'access' cost to the technology, discussed previously.

However, as can be inferred from the previous sections, the actual impact of 3D printing on the ability of entrepreneurs to devise and put in motion innovative business models strongly depends on what actual usage of 3D printing is made by entrepreneurs.

In this respect, Rayna and Striukova (2016b) outline that, in the general case, *rapid prototyping* and *rapid tooling* only have a minor effect on business model innovation, whereas *direct manufacturing* and *local fabrication* are potentially strong drivers of business model innovation. Firstly, because they provide businesses with means to deeply reconfigure most of the components of their business model. Secondly, the (virtual) lack of upfront manufacturing costs – and resulting on-demand production ability – enable companies to "rapid prototype" new business models (i.e. try successfully different new business models) and, in the long run, build adaptive and agile business models.

However, beyond the benefits of 3D printing for business model innovation in the 'general case', lies the question of which of those benefits actually apply to entrepreneurs, as opposed to larger organisations. This is a fair question, because technologies are often out of reach of entrepreneurs and smaller businesses because of their high price.[70] A further issue would be if only some usages of the technology – especially the 'least impactful' ones, i.e. *rapid prototyping* and *rapid tooling* – were accessible to entrepreneurs, while the most impactful ones – *direct manufacturing* and *local fabrication* – could only be accessed by larger businesses because of a higher cost. Instead, what was outlined in the previous sections is that 3D printing has reached a development stage at which all four types of usages have indeed become fairly accessible to entrepreneurs.[71]

As a matter of fact, the cases presented in the previous sections display significant evidence of Business Model Innovation. Using the Business Model Innovation Framework introduced in Rayna and Striukova (2016a),[72] Pressa Bottle (p. 17), for instance, is an example of innovation in both *value proposition* (through *product offering*) and *value creation* (through *value networks*). The 3D printed products sold through Shapeways (p. 19), show innovation in terms of *product offering* – a part of *value proposition*) – and *distribution channels* – a component of *value delivery*. MakerBot and Ultimaker (p. 20) have managed to compete with well-established incumbents, firstly by innovating in terms of *value creation*, by relying on far larger and wider *value networks*, i.e. open hardware communities and user contributions to manufacturing) and, secondly, by choosing an entirely new *market segment* – 'desktop' 3D printing, a part of *value delivery*. Finally, Fairphone (p. 30), besides the unique positioning of its core product (in itself a new *value proposition*, targeted at a different *market segment*, i.e. a new *value delivery*), took advantage of 3D printing by using the network of 3DHub 3D printers to manufacture accessories for its phones, which corresponds to a business model innovation in terms of *value creation* (*complementary assets, value networks*) and *value distribution* (*distribution channels*, in addition to the *market segment* innovation noted above). Another point of interest is that these cases of business model innovation indeed relate, for the most part, to 3D printing being used for *direct manufacturing* or *local fabrication*.

This last point is of particular interest, because, as noted in Rayna and Striukova (2016b), these latter two usages of 3D printing are key drivers of business model agility and reconfiguration – the authors speak

[70] e.g. while large companies in the automotive sector, for instance, have been using 3D printing for prototyping since the late 1980s, it will take another two decades for everyone to be able to enjoy the benefits of *rapid prototyping*.

[71] As noted earlier, while some 3D printers, especially those related to metals, remain prohibitively expensive, the wide range of services available – whether through platforms, bureaus, etc. – is such that owning one of such printers is not a requirement in order to benefit from the technology.

[72] Which represents business model innovation as being related to changes in either *value proposition, value creation, value delivery, value capture*, or *value communication*.

of “mobile business models” – as they enable companies to easily move upstream and downstream in their own markets (e.g. by taking over manufacturing, or, instead, outsourcing it), as well as horizontally – or ‘sideways – to other existing and new markets, which is a critical aspect of business model innovation (Giesen et al., 2007). As noted in Trimi and Berbegal-Mirabent (2012), one of the critical factors in startups’ survival relates to their ability to ‘pivot’ their business model. In this respect, the cases discussed in the previous sections tend to indicate that, indeed, such form of business model innovation enabled by 3D printing may be at play in the case of entrepreneurs. The SquareHelper case (p. 26) provides a good example of a business model moving downstream (since Chris Milnes took over manufacturing instead of outsourcing it), whereas the cases of Local Motors and Divergent3D (p. 31) are examples of a business model innovation by moving upstream (since, unlike traditional car manufactures, production is partly outsourced to other micro-factories). In terms of horizontal moves, besides the example of Square Helper – a clear move sideways to a new market, Shapeways (p. 19) and other online 3D printing platforms provide plenty of cases of startups that have moved away from their original field to new markets (e.g. from phone accessories to drone accessories).

Hence, in relation to prior findings in the literature, this research provides indications that the same benefits as those identified in Rayna and Striukova (2016b) are at play for entrepreneurs, despite their (generally) far more limited financial means. More importantly, in contrast to previous findings, what was outlined in the previous sections tends to indicate that those benefits may well be in fact more prevalent in the case of entrepreneurs than for larger and more established businesses. Indeed, as discussed in Section 5.2, one of the main shortcomings of *direct manufacturing* is that it is mainly economical for smaller volumes of production – anything above a few hundreds or a few thousands of units would make ‘traditional’ manufacturing more worthwhile. Such a low range of output is simply ‘below the radar’ for most established businesses, aside for those operating in very specific niche segments. As a result, this simply means that in the current state of development of the technology (and in the coming years), *direct manufacturing* and *local fabrication* are not going to be worthwhile, in the general case, in comparison to traditional means of production and distribution for most large enough companies. Considering the cases presented in the previous section, for instance, no large-enough company offering a ‘square-helper’ or a ‘mug-with-a-hoop’ would have ever used *direct manufacturing*, but would have, instead, mass-manufactured them.

In contrast, many entrepreneurs do face low demand at first, especially locally, and are likely to fall in the limited range where *direct manufacturing* (and, incidentally, *local fabrication*) are economically worthwhile. The consequence is that the current (and foreseeable) state of development of 3D printing technology is such that it can be expected to be a key enabler of business model innovation, but mostly for entrepreneurs and smaller businesses, as these are more likely to find it worthwhile making use of the most ‘disruptive’ forms – in terms of business model innovation – of usage of 3D printing (i.e.*direct manufacturing* and *local fabrication*), whereas larger businesses, in the general case, may be more prone to ‘stick’ with the least impactful ones (i.e.*rapid prototyping* and *rapid tooling*).

Table 3 provides a summary overview of the potential impacts, identified in this Section 5, of the four different types of usage of 3D printing – *rapid prototyping, rapid tooling, direct manufacturing, local fabrication* – for entrepreneurs in relation to the key entrepreneurial challenges outlined in Table 1.

6. Conclusion

The aim of this article was to assess the potential impact of 3D printing technologies on entrepreneurship. To do so, an extensive literature review was conducted and enabled to identify five types of critical challenges faced by entrepreneurs: New Product Development issues, technical issues, market issues, financial issues and business model issues. Based on an exploratory case-based methodology, the results of this research indicate that, overall, 3D printing may potentially be instrumental in helping entrepreneurs overcome all these types of challenges, at all stage of the production process (development, manufacturing and distribution).

However, it was also outlined that the extent of benefits of 3D printing for entrepreneurs may largely depend on the type of use – *rapid prototyping, rapid tooling, direct manufacturing, local fabrication* – that is made of these technologies. In particular, the cases considered in this research tend to indicate that *direct manufacturing* and *local fabrication* may be the most impactful for entrepreneurs.

direct manufacturing enables on-demand production, which, in turn, potentially gives rise to a *positive cash-flow* entrepreneurial model (i.e. ‘get paid, then manufacture’), which is the exact opposite to the traditional *negative cash-flow* model (i.e. ‘borrow money, manufacture, hope you will recover the money through the sales). This, in itself, may strongly alleviate the challenges faced by entrepreneurs, as the *negative cash-flow* model is at the source of all financial issues encountered by entrepreneurs (i.e. initial cost of production, lack of financial resources, equity gap, venture capital issues). On-demand production also reduces the need to devote large resources to marketing, as lack of discontinuity in production (and lack of stocks) allows for a more linear sales growth, making large-scale marketing less relevant.

Furthermore, *direct manufacturing*, through production on demand, provides means to alleviate both technical and New Product Development issues. Lack of technical resources, for instance, can be overcome both by the far larger value networks enabled by *direct manufacturing* (a driver of both crowdsourcing and mass customisation) and by outsourcing manufacturing to online 3D printing platforms and bureaus. Also, production on demand enables continuous product development, as each unit of the product manufactured can embed improvements based on the latest customer feedback.

Table 3
Summary overview of the potential impact of the different usages of 3D printing—*rapid prototyping* (RP), *rapid tooling* (RT), *direct manufacturing* (DM), *local fabrication* (LF)—on issues faced by entrepreneurs (lesser potential effects in brackets).

	RP	RT	DM	LF
NPD issues			✓	✓
NPD effect on growth and survival	✓		✓	✓
Complexity of NPD	✓		✓	✓
High failure rateof NPD	✓		✓	✓
Technical issues			✓	✓
Importance of tech. resources for NPD			✓	✓
Lack of technicalresources			✓	✓
Defective products	✓	(✓)	✓	✓
Market issues			✓	✓
Understand/meet customers expect. and needs	✓		✓	✓
Poor market research and analysis	✓	(✓)	✓	✓
Uncertain product value			✓	✓
Marketing issues (resources, activities)			✓	✓
Creating demand, market			✓	✓
and delivery channels			(✓)	✓
Competition			✓	✓
Market segmentation		✓	✓	✓
Product entry and exit			✓	✓
Scaleability		✓	✓	✓
Financial issues			✓	✓
Lack of financial resources	✓		✓	✓
Initial cost of production		✓	✓	✓
Equity gap	✓		✓	✓
Venture Capital issues	✓		✓	✓
Business model issues			✓	✓

Continuous product development permits not only to lower NPD complexity, but also to overcome the traditional high failure rate of NPD and subsequent defective products. Continuous product development is also a means to make up for poor market research and analysis, as products can be dynamically adapted as customers' expectations and needs become better known. Because of the constant unit cost of direct manufacturing, market segmentation can also be largely increased, thereby reducing the uncertain product value that potential customer may perceive.

Whereas lack of scaleability is a frequent cause of failure for entrepreneurs, this article has highlighted that 3D printing enables highly scaleable manufacturing, which makes the transition from the smallest volume of sales to significantly larger ones rather seamless. This scaleability, as well as the (virtual) lack of lead-time and upfront manufacturing cost, is also instrumental to reducing product entry and exit issues, which is critical to get ahead of competition.

Finally, it was discussed how *direct manufacturing* and *local fabrication* were key drivers of *distributed manufacturing*, hereby potentially reducing difficulties entrepreneurs have to access and build delivery channels, as *distributed manufacturing*, which implies products being manufactured close to customers, makes manufacturing part of the distribution process.

Although 3D printing is expected to be highly beneficial for entrepreneurs, some potential limits were pointed out in this research. In particular, the potential effects identified may not be as significant when the product may not be entirely 3D printed (which is still the case of many products). Yet, it was argued that when the 'non-printable' parts of the products are based on standardised and readily available components (e.g. Arduino circuit boards), the benefits of 3D printing may nonetheless be present. Product defects still remain a main challenge (Baumers et al., 2017), pre-processing and post-processing technologies also often lag behind (Despeisse et al., 2017). There is a lack of 'plug and play' solutions (Chaudhuri et al., 2019) and standards (Zheng et al., 2017), and intellectual property issues often arise(Lewental, 2017; Li et al., 2014).

As an outcome of this research, besides the obvious need to confirm empirically the exploratory results obtained, two main avenues for further research stand out. Since 3D printing sharply decreases the barriers to entrepreneurship, does this give rise to 'casual entrepreneurship', i.e. people occasionally (even maybe once) carrying out a venture around a particular product, while remaining employed otherwise? Examples in this article, as well as in Rayna and Striukova (2016b, c) appear to evidence this is indeed the case. A further avenue for research relates to 'community-based entrepreneurship'. Digital technologies, in particular Web 2.0 technologies and social media, have been highly instrumental in the development of community-based products (e.g. Wikipedia, Open Source Software). 3D printing has already enabled such products, for instance the RepRap self-replicating 3D printers. Yet, while online distribution costs can be negligible, this is not the case with physical products, which makes the question of commercialisation and entrepreneurship within a community worthy of interest.

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Supplementary material

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