UNIVERSITÉ DU QUÉBEC À MONTREAL

EMERGING BUSINESS MODELS AND MANUFACTURING DYNAMICS: ADDITIVE MANUFACTURING, MICROFACTORIES AND ONLINE MANUFACTURING PLATFORMS

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MODÈLES D'AFFAIRES ET DYNAMIQUES DE FABRICATION: LA MANUFACTURE ADDITIVE, LES MICRO-USINES ET LES PLATEFORMES DE MANUFACTURE EN LIGNE

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DEDICATION

To light and energy in all their forms

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

AI: Artificial intelligence

AM: Additive manufacturing

ASTM: American Society for Testing and Materials

3DP: Three-dimensional printing

CAD: Computer-aided design

CAE: Computer-aided Engineering

CAM: Computer-aided Manufacturing

CDMF: Customization driven microfactory

CNC: Computer numerical control

COMP: Closed online manufacturing platform

DIY: Do-It-Yourself

DMD: Direct metal deposition

EBM: Electron beam melting

ET: Emerging technology

FDM: Fused deposition modeling

IDMF: Innovation driven Microfactory

IJP: Ink jet printing

IoT: Internet of things

LOM: Laminated object manufacturing

MaaS: Manufacturing-as-a-service

MF: Microfactory

MOMP: Multisided online manufacturing platform

MS: Machine shops

OMP: Online manufacturing platform

RFID: Radio-frequency identification

SL: Stereolithography

SLM: Selective laser melting

SLS: Selective laser sintering

USAF: United States Air Force

ABSTRACT

This work examines how emerging technologies, such as three-dimensional printing (3DP) and online manufacturing platforms (OMPs), influence business models and manufacturing dynamics. To this end, this research is divided into three chapters. The first chapter discusses how 3DP is leading to the development of new business models. The insights from a multiple case study show that 3DP is not only influencing firms' value creation and value proposition; it also influences value communication and distribution to a greater extent than was reported in previous studies. According to our interviewees, 3DP is fostering the creation of new businesses and business models by enabling the creation of new services and products that were difficult to fabricate, or that were developed differently.

The second chapter explores the microfactory (MF) model, the elements that enable it and its implications on firms' economies of scale and scope. After examining patterns in online secondary sources, we argue that the high versatility and automation levels of some MFs may allow them to fill the gap between artisanal and mass production processes, increasing innovation, and facilitating the local on-demand fabrication of customized products.

The third chapter identifies, classifies and contrasts several MFs and OMPs. The results emerging from a multiple case study and experiential research suggest two main dimensions that differentiate MFs: automation and openness. We develop a taxonomy of MFs based on these dimensions. MFs with relatively low automation and high openness levels, MFs with high automation and low openness levels, and MFs with relatively low automation and low openness levels. There are also two types of OMP, closed (COMPs), which optimize the industrial installations and equipment of major manufacturers, and multisided (MOMPs), which connect customers with independent fabricators. MOMPs, in turn, can be low-end or high-end, depending on the market segments that they cater to.

Keywords: 3D printing, additive manufacturing, business models, microfactory, digital economies of scale and scope, digital manufacturing, local on-demand fabrication, online manufacturing platforms, case studies, experiential research.

RÉSUMÉ

Ce travail examine l'influence de plusieurs technologies émergentes, telles que l'imprimante 3D (I3D), et les plateformes de manufacture en ligne (PML), sur les modèles d'affaires et les dynamiques de fabrication. À cette fin, cette recherche est divisée en trois chapitres. Le premier chapitre traite de la manière dont l'I3D mène au développement de nouveaux modèles d'affaires. Les conclusions d'une étude de cas multiples montrent que l'I3D peut non seulement influencer la création de valeur et la proposition de valeur des entreprises ; cela peut également influer la communication et la distribution de valeur dans une plus grande mesure que celle rapportée dans les études précédentes. Selon les personnes interrogées, les I3D encouragent la création de nouveaux modèles d'affaires et impactent également les entreprises existantes. L'I3D permet la création de nouveaux services et produits.

Le deuxième chapitre explore le modèle des micro-usines (MU), les éléments qui le permettent et ses implications sur les économies d'échelle et de gamme. Après avoir examiné des sources secondaires en ligne, nous affirmons que la grande polyvalence et les niveaux d'automatisation de certaines MU peuvent leur permettre de combler l'écart entre les processus de production artisanale et de masse, d'accroître l'innovation et de faciliter la fabrication locale à la demande de produits personnalisés.

Le troisième chapitre identifie, classe et compare plusieurs MU et PML. Les résultats d'une étude de cas multiples et de « recherche expérientielle » suggèrent deux dimensions principales qui différencient les MU : l'automatisation et l'ouverture. Nous développons une taxonomie des MU basée sur ces dimensions. MU avec une automatisation relativement faible et des niveaux d'ouverture élevés, MU avec une automatisation élevée et des niveaux d'ouverture faibles, et MU avec une automatisation relativement faible et des niveaux d'ouverture faibles. Il existe deux types de PML, les plateformes fermées, qui optimisent les installations et équipements industriels des grands fabricants, et les plateformes multifaces, qui connectent des clients avec des fabricants indépendants. Les PML multifaces peuvent être bas de gamme ou haut de gamme, en dépendant des marchés ciblés.

Mots-clés : imprimante 3D, fabrication additive, modèles d'affaires, micro-usines, économies d'échelle et de gamme, fabrication numérique, fabrication à la demande locale, plateformes de manufacture en ligne, études de cas, recherche expérientielle.

INTRODUCTION

The central theme of this thesis focuses on the business models and manufacturing dynamics enabled by 3D printing (3DP)[1] and online manufacturing platforms. Since this is a broad theme, it had to be divided in several interrelated subjects: business models, emerging technologies, manufacturing configurations, and online platforms. Each chapter is framed within the central theme but emphasizes the different elements aforementioned, which added rigor and kept the project achievable. Hence, this research starts by focusing on emerging technologies (emphasizing 3DP) and how they generate value and affect the development of new and existing business models. These issues are explored at the micro level of firms in one single country in chapter 1, which tries to answer the question: *How is 3DP leading to the development of new business models?*

After having explained the implications of 3DP on business models, this research proceeds to explore, in chapter 2, the implications of some digital fabrication technologies and online platforms on production and manufacturing configurations. This chapter delves into the MF model—fabrication units that facilitate local production of custom products—and its intersection with crowdsourcing and crowdfunding platforms, digital twins and digital threads. The second chapter focuses on the question: *What are the implications of MFs for the economies of scale and scope of an industrial sector?* This chapter shows how technologies and platforms influence product scalability and diversification.

During the course of this research, we realized that online manufacturing platforms—notably the open platforms that connect fabricators with customers needing a product—

[1] Technology that manufactures products most commonly by superposing several layers of material.

were becoming increasingly relevant in the manufacturing landscape. Hence, chapter 3 explores the symbiosis between these platforms and microfactories. This chapter focuses on the questions: *What are the different types of MFs currently operating and how can we best classify and compare them? What are the different types of online manufacturing platforms currently operating and how can we best classify and compare them? To what degree and in what conditions do MFs and online platforms need one another to survive and thrive?*

This study intends to make practical, theoretical and methodological contributions. At the practical level, it shows how certain technologies can generate value for firms, shrink supply chains, enable local on-demand fabrication and reduce the risks and cost of innovation. At the theoretical level, it explores scale and scope economies in the digital domain, technology and service complementarity mediated by 3DP, and a way to classify certain fabrication units based on their openness and automation levels. At the methodological level, it introduces the concept of "experiential research" which consists of simulating or carrying out transactional activities with certain firms to gather information on how they work internally and interact with customers.

Overall, this research has a strong connection with the emerging literature on Industry 4.0 and can be situated within this field in terms of both level of analysis and focus. As regards the level of analysis, this research explores digital manufacturing technologies and online manufacturing platforms, how they enable firms to have complementary services and reduce the risk and cost of innovation and how they facilitate the transition to ecosystems that tend to be more open, integrated and automated. All these elements are at the core of Industry 4.0. As regards the primary focus, this study discusses new production configurations that allow manufacturing flexibility and scalability, the business models and strategies that accompany these configurations, and how they affect the transactions between firms and customers.

I was motivated to conduct this research out of curiosity, because it was aligned with my background in industrial engineering, and because I had many questions about 3DP and digital platforms: How do they work? What are their impacts? How do they interact among them? I was, somehow, sure that trying to answer these questions would take many months of research. Moreover, I could use my industrial engineering knowledge to link this research with key industrial challenges at the efficiency, sustainability, and scalability levels. How would 3DP and online manufacturing platforms help to solve these challenges? In what sectors would be more viable to solve these challenges by using emerging technologies? Which firms are the leaders in this digital transformation? By addressing all these questions I hoped to better understand the evolving dynamics of some industrial sectors, the business models enabled by new technologies, and some recent manufacturing configurations.

This is a thesis by articles, each one of them was turned into a chapter of this document. The first article was peer-reviewed, presented and commented at the 2016 IEEE European Technology and Engineering Management Summit (E-TEMS), Frankfurt, Germany and published in IEEE Explore. The second article was published in the June 2019 issue of the Journal of Manufacturing Technology and Management (JMTM). The third article was accepted by the JMTM and will be published soon. Each chapter focuses on a different level of analysis, the first one on technology, the second one on firms and the third one on industries. Moreover, the chapters are standalone units with their own introduction, justification, questions, methods, results and conclusions, but they are all tied to a general plan of exploring the business model transformations and manufacturing changes generated by emerging technologies and online platforms.

1. CHAPTER I: THE IMPACT OF 3D PRINTING ON THE DEVELOPMENT OF NEW BUSINESS MODELS

Abstract: Emerging technologies often trigger the development of new businesses. However, there is yet a little understanding on how this happens. This paper explores the effects of emerging technologies, specifically 3DP, has on the creation of new businesses by addressing the question: *How is 3D printing leading to the development of new business models?* To this end, this chapter discusses the elements of a business model and the features of emerging technologies and 3DP, and contrasts and analyzes previous literature regarding the effects of 3DP on business models. Afterwards, this chapter describes the qualitative method (multiple case study) used to gather, compile, and explore the influence of 3DP on the business models of 25 Colombian enterprises; 32 informants were interviewed. This analysis shows that 3DP influences the development of entirely new businesses and business models. Moreover, it affects differently the business models of existing enterprises. This chapter also explores the concepts of *technology complementarity* and *service complementarity*, which seem to be core elements to the success of enterprises centered on 3DP.

Keywords: 3D printing, business models, technology, case study, technology complementarity, service complementarity.

1.1. Introduction

To succeed in competitive global markets, firms constantly innovate their products and business models (Brynjolfsson & McAfee, 2014) and develop new capabilities (Westerman, Bonnet, & McAfee, 2014) accruing from their investment in emerging technologies (Simon, 2013) such as 3DP. According to many observers, this particular technology can enable "one of the next major technological revolutions" (Rayna & Striukova, 2016a, p. 214) and have "a huge and widespread impact on the world" (Garrett, 2014, p. 70).

3DP was initially used in product development to make prototypes, but now it is also being used to manufacture end-use products. General Electric, Boeing, and Ford, among other firms, are already using this technology to manufacture parts for some of their products (Gilpin, 2014). 3DP is now economically viable for the production of parts of engines, toys, drones, and even houses and prostheses. Moreover, 3DP has allowed some people to manufacture objects at home, and enables faster and cheaper product development cycle.

While much research has been done on the designs, printing techniques and materials, and applications of 3DP, little analysis has been done on how this is leading to the development of new businesses models. Yet, it is clear that 3DP provides new industrial opportunities and challenges (Bogers, Hadar, & Bilberg, 2016). Moreover, according to Rayna and Striukova (2016a), such a disruptive technology can trigger important changes in business models and ecosystems, but can increase the chances of failure when it is deployed without an appropriate business model.

This study aims to help close this gap in the literature and empirically explore the effects of 3DP at the business level. This paper is structured around the question: *How is 3D printing leading to the development of new business models?* In this research, a business model is a "representation of how a business creates and delivers value, both for the customer and the company."(Johnson, 2010, p. 22)

This study uses a multiple case study. Twenty-five Colombian enterprises were selected and classified into six categories: end-product manufacturers, manufacturers of 3D printers, firms that use 3DP for in-house prototyping, 3DP services providers, developers, and 3D printer distributors. The data were gathered by using semi-structured interviews, which were applied to 32 informants in 25 firms between July and August 2016. The interview audio files were transcribed, and the verbatim text of the audio files was codified and analyzed by using the textual analysis software ATLAS.ti. The codified extracts of the interviews were categorized into first order groups and second order themes to make sense of the information and to find patterns on how 3DP may be affecting the development of new business models.

Three main findings can be drawn from the assessment of the cases selected. First, 3DP is triggering the development of new businesses. In the group of end-product manufacturers, this technology has allowed the creation of new firms in the medical and art industry. All three cases that belong to this group developed an entirely new business centered on 3DP. The firms in the medical industry have centered their businesses on using 3DP to develop and manufacture 3D printed implants and prostheses in a cheaper and more efficient way. And the firms in the art industry use 3DP to manufacture miniature replicas of people and animals faster and with higher precision. The rise of 3DP has also allowed the creation of new firms that are exclusively dedicated to the manufacture of 3D printers or 3DP kits (group manufacturers of 3D printers) and firms that only distribute 3D printers and carry out technical assistance (group 3D printer distributors) and offer 3DP services (3DP service providers). Second, 3DP is influencing the business models of existing firms. The findings suggest that 3DP has enabled for some firms the possibility of saving time and money to customers and to offer a more integral service (value proposition), reduce the use of resources and processes in manufacturing (value creation) and facilitate the visualization of products before selling them (value communication). This is notably the case of the firm (plastic packaging) that uses 3DP for in-house prototyping and builds 3D printed prototypes before starting mass production. In the same vein, 3DP also affects the business models of new firms that belong to established industries such as the art and medical equipment (end-product manufacturers). Third, the impact of 3DP is not uniform across the six categories of firms that emerged from the cases selected. The information gathered suggests that 3DP influences more the companies that manufacture end-products, followed by companies that use the technology for prototyping and product development. The implications of 3DP for firms that distribute 3DP technologies are limited, mostly because their core business does not involve any kind of manufacture or prototyping.

1.2. Existing Theory and Empirical Works

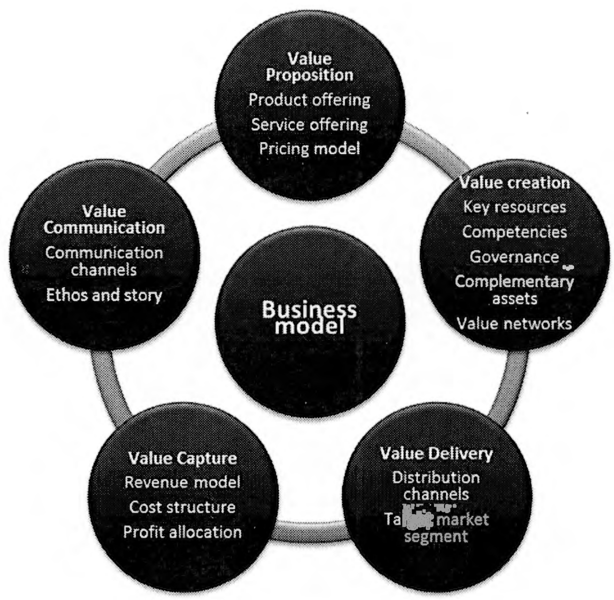
1.2.1. Business Model

There are several definitions of business models (Baden-Fuller & S. Morgan, 2010; Shafer, Smith, & Linder, 2005). According to Magretta (2002, p. 86), business models are "stories that explain how enterprises work. A good business model answers Peter Drucker's age-old questions: Who is the customer? And what does the customer value? It also answers the fundamental question every manager must ask: How do we make money in this business?" Shafer et al. (2005) see a business model as a representation of a firm's underlying core logic and strategic choices for creating and capturing value within a value network. For Johnson, Christensen, and Kagermann (2008) a business model is the interrelationship of a customer value proposition, a profit formula, key resources, and key processes to create and deliver value.

For Osterwalder and Pigneur (2002, p. 430), a business model has four pillars: the "what" the "who" the "how" and the "how much" of a firm; these pillars "allow to express what a company offers, who it targets with this, how this can be realized and how much can be earned by doing it." According to Osterwalder and Pigneur (2002), these pillars represent four main business model elements: the product, which describes a firms' value proposition; the customer relationship, which designates the relationship between a firm and its customers; the infrastructure management, which deals with the activities, resources and partners to provide the first two elements; and finally, the financial aspect, which describes how a company makes money through the other three elements. Baden-Fuller and S. Morgan (2010, p. 157) posit that one role of a business model is to describe "how a firm organizes itself to create and distribute value in a profitable manner." For Johnson (2010, p. 22), a business model is a "representation of how a business creates and delivers value, both for the customer and the company." In this work, I will use the definition proposed by Johnson.

In general, a business model involves five components or dimensions (Figure 1): *Value proposition*, that is, "the offering of products and services that are of value to customers" (Osterwalder, 2004, p. 43); *value creation*, the transformation of tangible and intangible resources to create products that customers want to pay for (Abdelkafi, Makhotin, & Posselt, 2013); *value communication,* which "ensures the delivery of value proposition as a message to the target groups, such as customers, investors, etc." (Abdelkafi et al., 2013, p. 12); *value delivery*, which defines the means by which enterprises establish interactions with the customer in order to provide the value (Abdelkafi et al., 2013); and *value capture*, which "describes how the value proposition is transformed into a revenue stream and then captured as profit" (Abdelkafi et al., 2013, p. 12). We will use these components to frame our analysis.

Figure 1. Components of a Business Model



Rayna and Striukova (2016a)

1.2.2. Emerging Technologies[2]

Rotolo, Hicks, and Martin (2015, p. 1828) define an emerging technology (ET) as a:

"Radically novel and relatively fast growing technology characterized by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous."

[2] This subsection was extracted from my synthesis exam "Regulating Emerging Technologies: The Case of Additive Manufacturing" which was later presented at the 2017 International Conference on Infocom Technologies and Unmanned Systems (ICTUS)(Montes, 2017)

Through a systematic literature review, Rotolo et al. (2015) identified five key attributes of an ET: radical novelty, coherence, uncertainty and ambiguity, relatively fast growth and prominent impact:

Radical Novelty: ETs are based on novelties derived from both technical revolutions (e.g., DNA sequencing technologies) and existing technologies used in a different way (e.g., wireless communication technology). A technology may be novel in one niche but not another.

Coherence refers to the amount of convergence with which technologies (Srinivasan, 2008 in Rotolo et al., 2015), research streams (Day and Schoemaker, 2000 in Rotolo et al., 2015), and actors and communities (Alexander et al, 2012 in Rotolo et al., 2015) are involved in ET development.

ETs are plagued by *uncertainty and ambiguity*. The technology standards are not well defined, there are no clear rules on how to regulate ETs, there is no universal model containing the features and functionalities of the ET, the optimal ways to produce and manage ETs are not completely settled, there are knowledge gaps, and there are many potential applications that have not been proven. The non-linear and multi-factor nature of ETs' evolution engenders uncertainty, making prediction difficult (de Haan, 2006; Mitchel, 2007 in Rotolo et al., 2015). Ambiguity arises because proposed applications are still fluid and even contradictory, which is exacerbated by the variety of outcomes that may occur depending on the meanings and applications people give to the technology (Mitchel, 2007 in Rotolo et al., 2015).

Speed: Relatively Fast Growth. According to Rotolo et al. (2015) ETs' relative growth can be measured by the number of actors involved (e.g., scientists, universities, firms, users), public and private funding, knowledge outputs (e.g., publications, patents), prototypes, products, and services, etc. A technology's fast growth needs to be contextualized, because it may grow rapidly in comparison with other technologies in the same domain.

Scale and Scope: Prominent Impact. ETs usually generate benefits for several sectors, create or transform industries, profoundly influence economies, and modify the dynamics between competitors (Rotolo et al., 2015). But the impact of ETs can be narrow or broad. They can reshape a given field (e.g., a new technology to detect diseases) or many fields (e.g., the Internet). The *scope* and variety of ETs cover a range of technologies that have converged in what Schwab (2016) calls "The Fourth Industrial Revolution." (Table 1). These technologies can be divided into physical, digital, and biological clusters. Moreover, they potentialize the broad power of digitization and information technology and are deeply interrelated; they are based on common technological progress and create synergies among them. The *scale* and volume of new technologies is also widening. There is an increasing quantity of enterprises producing and offering a specific new technology.

Table 1. Emerging Technologies that may Reach a Tipping Point by 2025

Physical	Digital	Biological
Autonomous vehicles	Internet of things (IoT)	Gene sequencing and editing
3D printing	Bitcoin and the Blockchain	Neurotechnology
Advanced robotics	Digital platforms	Designed beings
New materials	Artificial intelligence (AI)	Biotechnology
Energy storage	Quantum computing	Implantable technologies
Wearables and wearable Internet	Virtual and augmented reality	
Nanotechnology	Portable supercomputers	
	Big data for decisions	
	Smart cities and connected homes	
	Sharing economy	

Source: Schwab (2016)

1.2.3. 3D Printing

Additive manufacturing (AM) is defined by ASTM (2013, p. 2) as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." The printed object resolution depends on the layer thickness. Commonly used printing materials metals, polymers, ceramics, and biomaterials; wood, wax, paper, sugar, and chocolate are also used as feedstocks.

For Achillas, Aidonis, Iakovou, Thymianidis, and Tzetzis (2015), printing materials (feedstock) *can be liquid, powder, and solid based.* Liquid materials are used with stereolithography (SL), fused deposition modeling (FDM), and ink jet printing (IJP). Powder is used for selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), and direct metal deposition (DMD). Laminated object manufacturing (LOM) can use solid layers of any material category.

AM allows low-cost customization, flexibility, complexity, and assembly work reduction (Weller, Kleer, & Piller, 2015). It compares with other on-demand technologies such as digital books and music downloads, which enable consumers to order online, allow firms to profitably serve small market segments and operate with little or zero unsold inventory (Berman, 2012).

Gao et al. (2015) thoroughly explore AM status, challenges, and future applications, and H. Rogers, Baricz, and Pawar (2016) describe and classify services enabled by this technology.

1.2.3.1. Design: Economics of 3DP vs. Traditional Manufacturing

3DP economics differs in several ways from the economics of conventional design, manufacturing, and distribution.

Low prototyping costs: 3D printers have several advantages for developing prototypes and mockups, including ease of duplicating products, low cost, and speed (Berman, 2012). Since modifying prototypes becomes cheaper with 3DP, it's easier for marketers to test different versions of the same product based on customer comments and design feedback (Thilmany, 2009). While 3D digital designs can be displayed on a computer screen, many designers and customers may prefer examining and touching a real object before committing to a large investment (Berman, 2012). Prototype development costs and time are significantly reduced since no tools and dies are required in 3DP (Berman, 2012). For example, the shoe manufacturer Timberland used to spend roughly $1,200 and one week to develop a new sole. Using a 3D printer, a new model can be produced in 90 minutes for a cost of $35 (The Economist, 2009). 3DP has been broadly used for prototyping; however, this technology is becoming more reliable and precise; hence, some firms are using it to manufacture high quality, custom, and low-cost end products. 3DP is not always the cheapest solution. 3DP may be cheaper for manufacturing highly complex parts at low production volumes, but for fabricating products with simple geometries at high production volumes, traditional methods are generally more cost efficient.

High levels of product innovation: AM facilitates product innovation because design iterations are relatively inexpensive and parts can be rapidly produced. Product designs can be optimized according to their desired function rather than restricted from production technology or supply chain constraints (Berman, 2012; Lipson & Kurman, 2013). Additionally, the elimination of tooling resulting from AM adoption removes significant fixed costs associated with the introduction of new products, thereby promoting product innovation (Baumers, Dickens, Tuck, & Hague, 2016). Online 3DP platforms now allow a customer to see and download other user creations, which may favor the mixing of ideas and innovations. Despite the benefits of 3DP, it requires calibration and physical tests before printing an object, which may generate waste.

Faster, cheaper, agile design: 3D scanning allows easier, faster, and cheaper digitalization. It is only a matter of scanning a piece to get its 3D digital design. With traditional design, it was necessary to draw the object from the very beginning, which in some cases can be a complex and time-consuming task. 3D scanning, for example, allows artists and archeologists to reconstruct artwork and ancient pieces precisely, without compromising the physical structure of the object (Manferdini, Gasperoni, Guidi, & Marchesi, 2016). In the same vein, 3D imaging allows designers to conceive pieces and devices for which plans are not available. By using software, it is possible to scan a piece and reverse engineer it. The software generates a map of the piece's components and the possible ways they can be assembled.

1.2.3.2. Manufacturing

Extant literature suggests that AM is more advantageous than traditional manufacturing in certain markets (e.g., customized products), type of products (e.g., complex products), and industries (Berman, 2012; Petrovic et al., 2011; Weller et al., 2015).

High customization and product flexibility: Product flexibility refers to the firm's ability to efficiently shift capacity from one product line to another in any order (Sethi andSethi,1990 in Weller et al., 2015). 3DP enables product flexibility and customization without cost penalties (I. Gibson, Rosen, & Stucker, 2010), which potentially yields an increase in perceived product value and, thus, higher willingness to pay. As a result, firms can charge a premium price (Weller et al., 2015). Moreover, AM will likely enable firms to realize strong economies of scope in product differentiation (Weller et al., 2015). However, increasing the range of printing materials and the possibility of mixing several materials in one object still is in progress.

Reduced product complexity: By adding material layer by layer, AM has fewer process and design restrictions, allowing the design of functionally optimized products

(Petrovic et al., 2011). Moreover, one important AM advantage is its capability of producing prototypes of complex shaped objects such as elements with moving parts (Vinodh, Sundararaj, Devadasan, Kuttalingam, & Rajanayagam, 2009). By using AM, product complexity is not a problem; it costs virtually the same to produce a complex engine piece than a block with the same volume, material, and estimated printing time. However, for firms that require high precision products, the resolution of some 3D printers may not yet be enough.

Effectiveness for small production runs: In contrast to injection molding processes that require costly molds, 3DP entails relatively low fixed costs (Berman, 2012). As stated above, since 3DP does not need expensive tooling, forms, or punches, it is particularly cost effective for small production runs. This enables firms to profitably use 3DP to fill custom orders and serve niche markets (Berman, 2012).

Less energy consumption in certain conditions: AM energy consumption may be lower than that of traditional manufacturing at low production volumes. According to the Advanced Manufacturing Office (AMO) of the U.S. Department of Energy (2012a), AM saves energy by eliminating production steps, using less material, enabling by-product reuse, and producing lighter products. Moreover, the AMO (2012b) indicates that remanufacturing parts through AM and surface treatment processes can also return end-of-life products to as-new condition using only 2–25% of the energy required to make new parts. However, according to Yoon et al. (2014), at high production levels, AM energy consumption is estimated to be ~100-fold higher than that of conventional bulk-forming processes. As the volume of identical production parts increases, the per-part energy consumption for injection molding and machining decreases significantly.

Higher resource efficiency? With AM, less material is used to produce an object, and unused raw material can be (re-) used to produce other objects (Barz, Buer, & Haasis, 2016). Therefore, less material is required, which increased resource efficiency (Liu, Huang, Mokasdar, Zhou, & Hou, 2014). In comparison with subtractive technologies, which use multi-axis cutting machines to carve plastics and metals, 3DP wastes less material: no scrap, milling, or sanding (Berman, 2012). Prior studies suggest that 95% - 98% of 3DP waste material can be recycled (Petrovic et al., 2011). In contrast to traditional manufacturing, AM could reduce manufacturing water consumption, thus is more sustainable (Cozmei & Caloian, 2012). However, AM may also have disadvantages. In addition to being more energy-intensive, as per the previous point, it can augment the pace of new product launching, rendering old but functional products rapidly "obsolete," which may have negative environmental impacts.

Cheaper and agile quality control: 3D scanning allows more efficient and low-cost quality control. Traditionally, objects are inspected manually on the production line. With rapid and precise 3D scanning, inspection is automatic, requiring fewer human interventions and interruptions. This generates better quality control, increased productivity, and cost savings.

1.2.3.3. Distribution

Higher volume flexibility and product variety, and less inventory: Volume flexibility describes a firm's ability to easily change production output with minimum cost penalties (F. F. Chen & Adam, 1991). Lead times for manufacturing single batches of products can be reduced; variants of the same product can be manufactured in any sequence without additional change over time or switching costs. AM allows custom product manufacturing without costly inventories of semi-finished and finished goods (Berman, 2012).

1.2.3.4. 3DP and Health

Despite the advantages of 3DP at the production level, this technology poses several health risks to users. Mendes et al. (2017) compiles some of these health risks. First, more people are exposed to harmful emissions and chemicals. Because of the low cost of some 3D printers, more people can have them in their homes, offices or schools where they do not have the necessary training to reduce the impact of dangerous fumes and particulate material. Second, low-cost 3D printers usually do not have the built-in containment required to reduce the dissemination of harmful gaseous emissions. This problem is even worse when the facilities where the 3D printers are located do not have proper ventilation and cleaning systems suited to handle particulate matter. Third, depending on their composition, some polymers used as feedstock during the 3DP process contain carcinogens and respiratory irritants that can reach the lungs and other vital organs. For Mendes et al. (2017), when operating 3D printers it is always important to follow precautionary measures and use air filtering systems especially when several printers are used simultaneously during long periods.

3D printed parts such as prosthesis or plastics used on the bioengineered culture systems may also have a negative impact on health (de Almeida Monteiro Melo Ferraz et al., 2018). They have been reported to be toxic to zebrafish embryos (Oskui et al., 2016), to cause allergic and inflammatory responses in mice (Popov et al., 2004), and to be toxic to certain cells (Inoue & Ikuta, 2013). Besides respiratory issues, 3DP has also been linked to skin problems (Chan et al., 2018): hypersensitivity pneumonitis associated with nylon powder used in 3D printing (Johannes, Rezayat, Wallace, & Lynch, 2016) and asthma (House, Rajaram, & Tarlo, 2017), as well as two cases of contact dermatitis (Creytens, Gilissen, Huygens, & Goossens, 2017). In a pilot study, Chan et al. (2018) found that 95% of workers using 3DP reported respiratory symptoms, 20% reported cutaneous symptoms and 17% reported headaches occurring more than once per week in the past year.

1.2.4. Industry 4.0

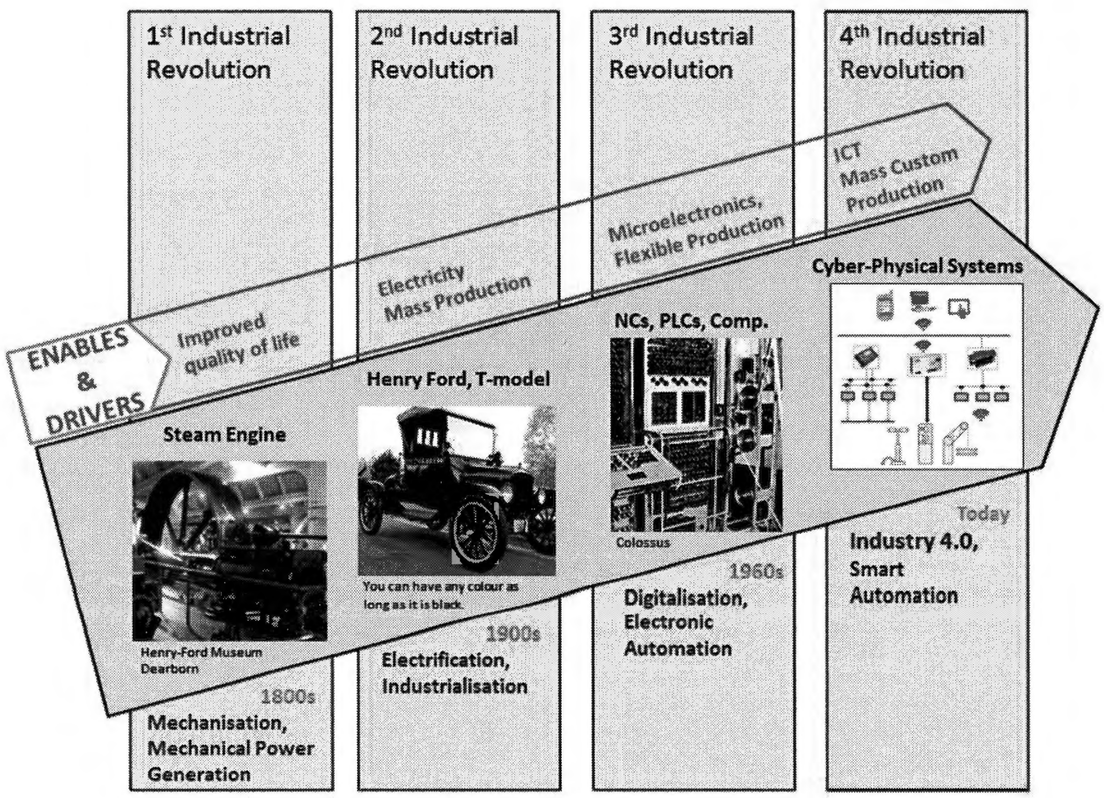
Industry 4.0 (I4.0) is a relatively recent concept that has gained popularity in industry, government, and academia. I4.0 promises to transform the manufacturing industry as we know it by employing data-driven, automation, sensors, and cloud computing technologies to optimize and control production in real time. There is a reason for this increasing popularity. Firms aim to become more productive, efficient, and profitable. They see the potential of I4.0 to achieve these goals through digitalization, which involves the combination of advanced connectivity, artificial intelligence, 3D printing, and the internet of things to transform their businesses. In 2016, for example, the consulting firm PwC (2016) surveyed 2,000 firms from nine major industrial sectors and 26 countries and found that 33% of the firms have already high levels of digitalization and 72% will be highly digitalized by 2020 (Geissbauer, Vedso, & Schrauf, 2016). At the same time, policy makers try to design policies to increase countries' competitiveness and economic growth by optimizing production and by manufacturing products with more value added. Several policy instruments are relevant: the US "Advanced Manufacturing Program," the "China Manufacturing 2025" plan, and the Korean "Manufacturing Innovation 3.0" smart plan. Scholars try to understand the implications of I4.0 and generate applications for the I4.0 realm.

In the age of Industry 4.0 objects become smart and communicate between them (Energie, 2015): they have bar codes or RFID chips containing important information that computers can and forward to the cloud and assure that everything runs efficiently; both the physical and the virtual worlds collide into cyber-physical systems.

1.2.4.1. From Industry 1.0 to Industry 4.0

Rojko (2017) describes the three industrial waves that preceded I4.0 (Figure 2). The first wave began with the mechanization and mechanical power generation in 1800s, which allowed transition from manual work to mechanical processes; mostly in textile industry. The second wave centered on the generation and use of electricity, which enabled industrialization and mass production in 1900s; product variety and production flexibility was neither a priority nor easy to reach. The third wave started with the digitalization and the use of microelectronics in 1960s, which facilitated both automation and flexible production; programmable machines facilitated product variety. Today, the fourth Industrial Revolution is centered on Information and Communications Technologies (ICT), which enables smart automation of cyber-physical systems with decentralized control and advanced connectivity (IoT functionalities). Hence, it is possible to reach flexible mass custom production.

Figure 2. Four Industrial Revolutions



Source: Rojko (2017)

1.2.4.2. Benefits and Key Components of Industry 4.0

According to Roblek, Meško, and Krapež (2016), the I4.0 has several benefits and components. Regarding the benefits, it can increase competitiveness via smart equipment, facilitate decision-making through actionable and real-time information, and increase resource and energetic efficiency (Heck & Rogers, 2014). The Industry 4.0 involves several components: cyber physical systems (real and virtual world connections), the smart factory; machine communications (M2M) and smart products (Kagermann, 2015).

Table 2. Fundamental Concepts of Industry 4.0

Expression/fundamental concept	Explanation
Smart factory, smart manufacturing, intelligent factory, factory of the future	The smart factory will be more intelligent, flexible, and dynamic. Manufacturing will be equipped with sensors, actors, and autonomous systems. Machines and equipment will have the ability to improve processes through self-optimization and autonomous decision-making.
New systems in the development of products and services	Product and service development will be individualized. In this context, approaches of open innovation and product intelligence, as well as product memory, are of outstanding importance.
Self-organization	In manufacturing, new processes can change entire supply chains. These changes will have an impact on changing processes from suppliers to logistics and to the life cycle management of a product. Along with all these changes, manufacturing processes will

	be closely connected across corporate boundaries. These changes in supply and manufacturing chains require greater decentralization from existing manufacturing systems. This fits with a decomposition of the classic production hierarchy and a change toward decentralized self-organization.
Smart product	Products are inserted with sensors and microchips that allow communication via the IoT with each other and with human beings. Cars, T-shirts, watches, washing powder, and so on, are set to become “smart” as their makers attach sensors to their packaging that can detect when the product is being used and can communicate with smartphones when scanned. Smart products are eliciting the question of invasion of privacy and, consequently, personal safety.
New systems in distribution and procurement	Distribution and procurement will increasingly be individualized.
Adaptation to human needs	New manufacturing and retailers’ systems should be designed to better fit human needs instead of the reverse. It is suggested that these systems may well be a combination of robotic-like tools such as personal intelligent agents, such as Siri, Viv, Cortana, Google Now, and others, and the IoT. That can become the dominant model of the interaction between buyers and sellers.

Cyber-physical systems	Systems will integrate computation, networking, and physical processes. Embedded computers and networks will monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa. An example is control of vital human functions that allow urgent health care through mobile applications, sensors in clothing, and sensors and surveillance cameras in flats.
Digital sustainability	Sustainability and resource efficiency are increasingly the focus of the design of smart cities and smart factories. It is necessary to respect ethical rules when using private information. These factors are fundamental framework conditions for successful products and processes.

Source: Adapted from Roblek et al. (2016)

1.2.5. Existing Empirical Work

Some studies have addressed the effects of 3DP on the emergence of new business models. Garrett (2014) argues that 3DP can "dramatically change business models, shift production location, shrink supply chains, and alter the global economic order" (p. 70). Garrett (2014) only explains the policy implications of 3DP; he does not explain in detail and based on evidence how and why this technology allows the development of new business models.

Prause (2015) tries to show the direction that new and existing business models must take to benefit from Industry 4.0. Unlike the lack of empirical evidence of Garrett (2014), Prause (2015) combines interviews and case studies to advance his research question. He concludes that “new value chains open the way toward complex and intertwined manufacturing networks, which will change the roles of designers, physical product suppliers and the interfaces with the customer causing a fragmentation of the value chain.” Prause (2015, p. 161) is not focused only on 3DP, rather he encompasses all of Industry 4.0, consequently his approach is quite general, and the specific effects of 3DP on development of new business models are not covered in detail. Moreover, his paper is mostly focused on the value chain, and does not analyze business models enabled by 3DP.

Bogers et al. (2016) explore the effects of 3DP printing on business models in the consumer goods manufacturing industry. They propose that 3DP affects business models by changing “the role of the consumer in consumer goods manufacturers’ business models with a particular implication being that supply chains are becoming more distributed and decentralized to enable more personalized production of consumer goods.” Consequently, “productive activities shift from the manufacturer to the consumer, which leads to a need to decentralize and decouple the organization of the manufacturer’s supply chain to embrace the central role of the individual consumer in the value creation-capture process” (p. 225). The study of Bogers et al. (2016) is limited to 3DP technologies and their implications on supply chains in the consumer goods industry. In the same vein as Bogers et al. (2016), Kostakis and Papachristou (2014) conclude that 3DP enables local, customer-centered production and collaborative productive processes of designing, programming, and manufacturing.

Rayna and Striukova (2016a) explore the impact of 3DP on the five key business model components in four different progressive stages of adoption of 3DP: rapid prototyping, rapid tooling, direct manufacturing, and home fabrication. They argue that rapid prototyping and rapid tooling have a limited impact on business models: they merely speed up the process but without changing it significantly and they may affect cost structures but their impact on value capture is unlikely to be significant. The authors note that the increasing affordability of 3D printers could increase the pace of competition by bringing rapid prototyping to the masses. Conversely, direct manufacturing of end-use products with 3D printers and home fabrication (i.e., personal 3DP) may be significantly more disruptive because they are likely to increase value creation (as a result of an increase in complementary assets and value networks) and value delivery (as a result of the access to new delivery channels and market segments) (Rayna & Striukova, 2016a). The authors conclude that 3DP leads an increasing intensity in competition from SMEs, individual entrepreneurs, and "prosumers" and enables a rapid rate of business model innovation. Despite being one of the works that best describes the influence of 3DP on the development of new business models, this study does not address in detail the question of how 3DP actually shapes the development of new business models specifically from the 3D printer manufacturers, end-product manufacturers, 3D printer distributors, and 3DP services providers side.

Even though these studies discuss the implications of 3DP for the emergence of new business models, some of them lack a solid empirical evidence and are focused on just one element of a business model, value distribution, while other elements (value proposition, value creation, value capture, and value communication) are overlooked. Moreover, in general, these studies do not provide a rich account on how and why 3DP is leading to the development of new business models.

1.3. Methods

The analysis was tied to the factual information gathered. The research was developed inductively with no prior research assumptions but with certain notions about how 3DP might be influencing business models.

1.3.1. Research Strategy

The research question was answered through case studies. According to Yin (2009, p. 38) a case study is "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident." Case studies work well when a research question seeks to explain present circumstances and how a phenomenon works (Yin, 2009). Moreover, case studies allow researchers to retain the holistic and meaningful characteristics of real-life events; they are commonly used in social science disciplines such as management and marketing (Yin, 2009).

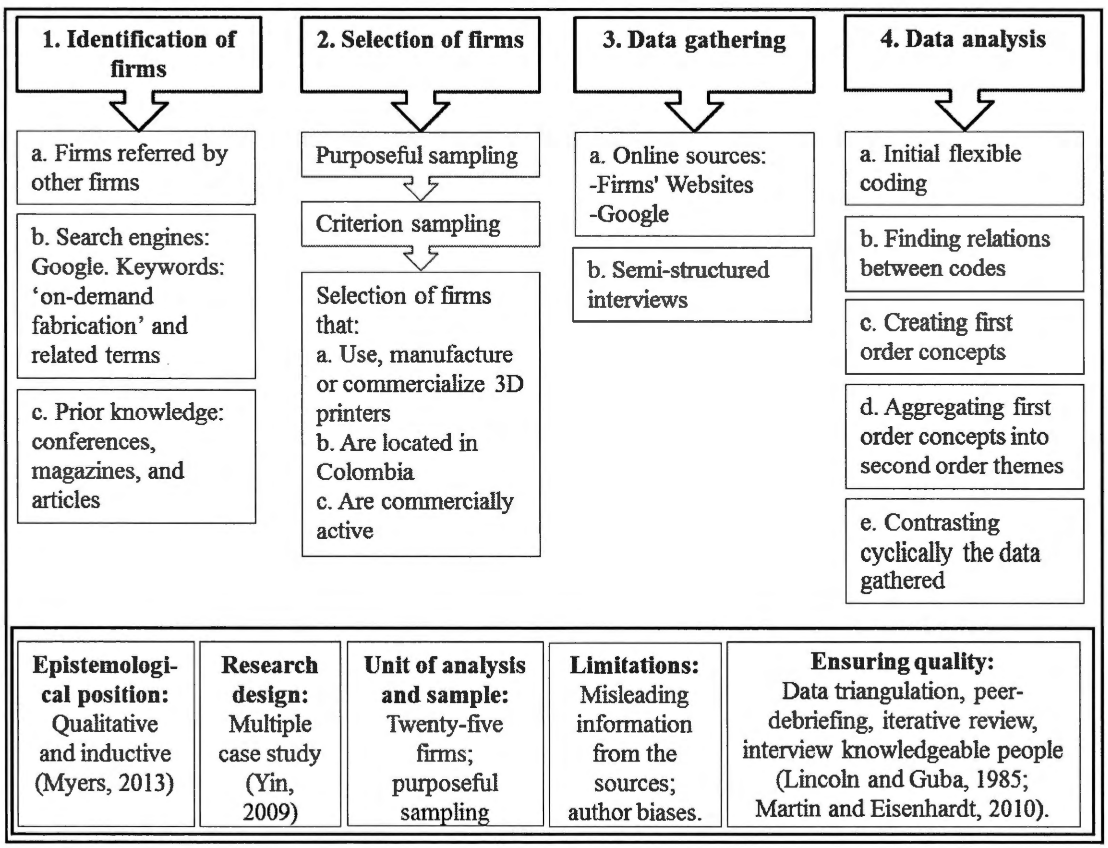
1.3.2. Unit of Analysis and Sample

This research was based on a *multiple case design* (Figure 3). Twenty-five companies were analyzed, which facilitated the analysis of the influences of 3DP on each case, and the analysis of the similarities and differences of these influences across enterprises. *Purposeful sampling*[3] was employed to select which enterprises to study and which people to interview, resulting in a selection of information-rich cases that provided relevant information (Patton, 2002). The resulting sample included firms that: had public information on the Internet, were referred by other firms, agreed to provide information, and/or belonged to different industries. Thirty-two informants from 25

[3]Method to identify and select information-rich cases based on several criteria (e.g., extreme, typical, and heterogeneous cases).

enterprises located in 4 cities were interviewed from July-August 2016[4]. The names of the interviewees have been changed in this document, so as to protect their anonymity. The product and service offerings of these firms involve the manufacturing, commercialization, and/or use of 3DP. The interview audio files were transcribed and analyzed using ATLAS.ti, a textual analysis program. Along with the semi-structured interviews with heads of product development departments or CEOs of each enterprise, data triangulation was also applied (i.e., contrasting several sources of information such as websites and press releases).

Figure 3. Methods: Step by Step



[4]There are more informants (32) than firms (25) because in some cases I interviewed more than one person per firm.

1.3.3. Data Analysis

The data were analyzed, while being gathered, by using the coding guidelines proposed by Miles, Huberman, and Saldaña (2014) and Charmaz (2006). Coding means "categorizing segments of data with a short name that simultaneously summarizes and accounts for each piece of data" (Charmaz, 2006, p. 43). To provide rigor and reliability these guidelines were integrated into six iterative and overlapping phases:

1. *Initial flexible coding:* In this phase I identified the codes that emerged from the transcription of the interviews. I used two of the six methods of coding proposed by Miles et al. (2014). *Descriptive coding* which allowed summarizing concepts and identifying general topics that emerged from the transcript, and *in vivo coding*, which allowed using the words of participants as codes. In this phase, I defined and refined each code while coding the first interviews and I remained flexible to new emerging codes.

2. *Finding relations between codes:* In this phase, I identified the codes that overlapped each other or that were related in some way. I established the type of relation between these codes (e.g., inclusion, exclusion, causality) and counted the number of quotes for each code (e.g., Malina & Selto, 2001).

3. From the analysis of relationships among codes and the frequency of quotations per code, I abstracted *first order concepts*, which represented the first level of aggregation of codes (e.g., Corley & Gioia, 2004). This way I could obtain both, general topics/categories that emerged from the data and the relations between the elements of these categories.

4. I intended to aggregate the *first order concepts* in more general categories of abstraction or *second order themes* (e.g., Corley & Gioia, 2004).

5. While the prior phases were in progress, I *contrasted cyclically* the data gathered, the emerging theoretical constructs, and prior literature to refine the abstractions, relations, analysis, and aggregations with a greater extend and to build a better emerging theoretical framework (e.g., Martin & Eisenhardt, 2010).

I *synthesized and analyze*d the resulting set of first order concepts and second order themes in a coherent way. This process of synthesis and analysis involved both, a description of the categories that emerged from the data and an analysis of the relationships between them.

1.3.4. Quality Conditions

Some of the guidelines proposed by Yin (2009) and Lincoln and Guba (1985) were applied to increase the overall quality and trustworthiness of the research. *Data triangulation* was implemented. This technique may provide more rigor to the research, enhance accuracy, help to reduce information bias, add consistency to the data analysis, and may result in more valid and reliable findings and theories (Martin & Eisenhardt, 2010; Miles et al., 2014; Yin, 2009). To improve *transferability (external validity)*, a database with the information gathered during the inquiry was developed and an exhaustive explanation of how the data were used to arrive at the conclusions was written. To increase *dependability (reliability)*, the method proposed by Martin and Eisenhardt (2010) to *reduce informant bias* was applied. This method consists of interviewing highly knowledgeable informants who are encouraged to focus on recent and concrete events to enhance accuracy, reduce recall bias, and avoid speculation. Moreover, the interviewees and their firms were treated anonymously to encourage frankness. To verify the accuracy of the information gathered, the answers to certain questions were compared with the answers provided by other informants inside or outside the company.

1.4. Findings

Six business types based on 3DP were identified according to the core function it has in the firm: manufacturers of 3D printed end-products (end-product manufacturers), manufacturers of 3D printers, firms that use 3DP for in-house prototyping, 3DP services providers and product developers (developers), and 3D printer distributors. Each business type (Table 3) has been affected differently by 3DP technologies.

Table 3. Types of Enterprises

Classification	Companies	Informants	Field
End-product manufacturers	3	4	Medical technology, art
Manufacturers of 3D printers	4	6	3DP manufacture
Firms that use 3DP for in-house prototyping	1	2	Plastic packaging
3DP services providers	11	11	3DP services
Developers	5	8	Product development
3D printer distributors	1	1	3DP Commercialization
Total	**25**	**32**	

1.4.1. 3D Printing and the Development of New Business Models

1.4.1.1. End-product Manufacturers: The case of medical technology and art firms

Based on the interviews, we can conclude that 3DP has allowed the development of new businesses and has influenced the value creation, proposition, communication, and distribution (business model) of some firms (Table 3); value capture has not been affected significantly. Three of the cases analyzed have developed an entirely new business based on 3DP. One is a company that 3D prints plastic replicas of people and animals by scanning and printing a miniature version of them in high resolution. Another is a company that prints customized implants and population-specific implants (standard implants) for the musculoskeletal system that matches the anatomy of patients of specific countries. And the third firm 3D prints customized surgical guides, bio-models, and craniomaxillofacial implants.

Concerning ***value creation***, Fred, from the company that makes custom implants, posits that managerial processes have also been affected: " … let's say we had to find a much more experimental and lean management model because technological predictions for this industry become almost obsolete in a year from now. Then, we rather do a monitoring process of emerging technologies and research." According to Mark, from the company that manufactures bio-models and custom implants, the customer relationship is even closer: "Our work is about sitting down to design a bone … then we have to meet the people, the dramas, the problems, and the joys … and all that's behind." Mark says that the production process was affected too: "[3DP] also increases the speed of the product development process … product development time is drastically reduced by using 3DP." For Mark, less material is required now to produce the same implants they made before by using other methods.

The value proposition is stronger than before. According to Mark, printed implants may reduce total cost and surgery time, and the patient is affected to a lesser extent (value proposition): "For the health system there is a cost reduction because a custom implant does not require another surgery. Skull surgeries that are carried out with titanium or acrylic plates [rather than custom implants] tend to have problems and the surgeon needs to operate again. That costs a lot of money because surgery time is almost the highest hospital expense." For Mark, "Having a custom implant for skulls reduces surgery time by 60%. Besides, it reduces the time that a patient is exposed to infections and it allows a less intrusive surgery." Furthermore, 3DP has increased the diversity of solutions for patients with implant needs.

According to Fred, 3DP impacted the entire business: "I would say [the impact of 3DP] is generalized." Regarding ***value communication***, Fred adds that 3DP may have increased sales and influenced customer relationships: "This possibility has generated a major increase in sales... The customer relationship changed completely. Working with custom implants forced us to have a higher-level relationship with our customers. The doctors stop being passive buyers and become members of a design co-creation process, and in that sense a normal seller no longer can speak with the doctor, it has to be a vendor who understands what he is co-creating with the doctor. Then, in the business process, that was a great transformation."

Value capture has also been affected, but in a lesser extent. For Fred, making 3D printed implants has influenced their revenues, it has generated "an important source of income."

As a consequence of the implant's novelty and the need for reducing risks associated with implant installations and post-surgery care, the target market segment ***(value distribution)*** of the two companies that produce custom implants is quite focused and closed in some cases. One of the companies has an accreditation process that permits only the most experienced surgeons to implant their 3D printed solutions: "for one of our products, the focus is to create a select group [of surgeons]... those who are more prepared, those who earn more money, and the most renowned get the accreditation and may install our dental aligners. This is like our target." Another company is building a community as a marketing and network creation tool: "We have created a community of early adopters, we meet annually at a conference where the community exchanges experiences and ideas ... Marketing has become more about creating a community of users and 3DP fans than about simply pushing doctors to buy a technology and a product."

Table 4. How 3DP is Influencing Business: End-product Manufacturers

Quotation	First order concepts	Business model components[5]
"We have a very close relationship with the special materials group of the company that provides us the technology, and we do joint research projects where we develop special materials for our solutions." (Fred, from the company that makes customized implants)	Research (Key activities)	Value creation
"For us it was previously impossible to develop custom treatments, simply because manufacturing methods were unfeasible for that" (Fred) "3D printing allows the cost of manufacturing complexity to drop to zero. On 3D printing, it costs the same to make a rectangular plastic block than to make a skull—with all the complex structures the latter has. And that's the great thing: the cost of making models and pieces of high complexity is nil ... And that is to us the great differentiator of 3D printing" (Fred)	Complexity reduction (Key Processes)	
"It has to be clear that 3DP is not a matter of volume... And that means many things at the administrative level ... continuous improvement, constant monitoring of processes, innovation and development of new products... It changes the service I offer, what I offer, and how I can satisfy the customer needs. Because	Management	

[5] These are equivalents to the second order themes explained in the methodology section.

each client is different. That's the philosophy of what is behind the company." (Mark)		
"We had a 5-axis milling machines with which we made customized implants. That was a very long process, a lot of material was wasted... That's another reason why we now use this new technology [3DP]" (Mark) "Say it is 20% more expensive [to produce an implant in a milling machine rather than in a 3D printer]. The difference is not high, but there is no material wasted with the 3D printer." (Mark)	Less wasted material	
"This is a 3D experience... This is different. People get very excited when you take the picture, when you go and tell them what you are doing. This is a super cool experience because it's something a little magical ... an affiliation between the customer and the company is created" (Ralph, from the company that prints replicas of people)	Novelty	**Value proposition**
"[We] always focus on the issue of support and flexibility ... Being a Colombian company, we can customize some design variables for special patients." (Fred)	Customization and flexibility	
"Going to surgery with a customized 3D implant enables much lower costs of surgery and greatly improves surgical outcomes" (Fred)	Cost reduction	
"In some cases [the time of surgery] can be reduced by 60%."... "Previously, for some fibula surgery, the surgeon had to cut the fibula, then blend a metal plate by hand, and then install it on the bone ... Such surgeries took between 12 and 14 hours. They can be	Time reduction	

done today with 3D printing and custom implants in 4 hours" (Fred)		
"In dentistry we use 3D printed bio-models for diagnosis—and to show to a patient how his bone is doing—, because specialists have a problem and is that their patients think they are fine… Patients say 'here I have bone for an implant,' but the difficulty is that the implant needs a bone with enough space …, otherwise the implant cannot be installed. Then specialists use the 3D bio-models to make a diagnosis and to prove to the patient that they need the implant" (Mark)	More realistic than before	
"[3DP] is allowing us to offer solutions to patients for whom there was no solution before." (Fred)	Product/Service Diversification	
"The development of a custom implant is a co-creation process where engineers participate actively part of the process of treating the patient. Then we have the surgical planning software, and engineers constantly talk with surgeons and plan the cases." (Fred)	Co-creation and strong relation with customers (Customer relationship)	**Value communication**
"[3DP] has generated an important source of income." (Fred)	Sales	**Value capture**
"We handle only raw material inventory… All we have planned in terms of inventory is … the material needed to work" (Mark) "We have zero inventories of custom implants, hence logistics costs are almost zero … That greatly reduces the operating and transaction costs of treating a patient" (Fred)	Low levels of inventory	**Value distribution**
"At the beginning, treatments rather than products started to fail … Lack of care during surgery, lack of	Accreditation process	

knowledge to take care of the patient… That forced us to change a bit the model and we started to provide accreditation; only doctors with accreditation could take care of patients" (Mark)		
"As implant technology is still a market segment of early adopters, … marketing grew from a marketing push to community marketing" (Fred)	Building a community of early adopters	

1.4.1.2. Manufacturers of 3D printers

3D printer manufacturers' core business is to assemble or manufacture 3D printers. They may also distribute fully assembled 3D printers or 3D printer parts that buyers assemble by themselves. Some 3D printer manufacturers offer additional products and services such as 3DP workshops, product development consulting, and makerspaces renting. Makerspaces are places where people can use machines and software to make their own manufacturing prototypes and projects.

Regarding ***value creation***, 3DP and other recent manufacturing technologies give 3D printer manufacturers the *flexibility to easily fabricate different kinds of devices*. Moreover, they have the *capability to improve or modify substantially their own technological resources*. For Charles, founder of a firm that manufactures 3D printers, 3DP accelerates operations, increases a company's autonomy, and reduces costs: "We can have almost immediate versions of some products without resorting to other tools or third parties, which may lead to higher costs. So, we're talking about speed and economy. 3DP even gives us an interesting visibility."

3D printer manufacturing is only one of the many new kinds of businesses that have emerged because of 3DP and that are being influenced by this technology (Table 5). As regards new ***value propositions,*** 3D printer manufacturing has facilitated the *deployment of a new technology* to satisfy the prototyping needs of 3DP enthusiasts. In the past, this technology was too expensive, and almost exclusively available to large companies. Moreover, 3D printer manufacturers satisfy the *training needs* of people wanting to use 3DP to develop products on their own. As stated by Charles "We do not just buy and sell technology, we go much further. We educate people on how to make that technology (3DP) themselves, and how to use that knowledge to innovate and develop new things." Some 3D printer manufacturers also offer spaces where customers can use 3DP, other manufacturing technologies, and expert support to *materialize their ideas from the very beginning until the end* (manufacture) with almost no prior knowledge.

3D printing technologies are relatively new and most people do not know how to use them, which has had an impact on 3D printer manufacturers' ***value communication***. Such firms are usually forced to offer technical support that can last several weeks or months until buyers learn how to use and repair the 3D printers, which creates a *close relationship with customers*. Often, technical support is offered virtually through YouTube and Teamviewer[6], and in a few cases, in person. Charles explains: "We rely a lot on digital media, we have our own website. Lately, we have been working on our YouTube channel to offer the solutions to the most frequently asked questions... That is the first channel and possibly the most widely used right now... Within our management system, we offer a remote three-months technical service for free after the purchase. Then, people can call or write to us. We take control of customer machines with applications like Teamviewer to provide support." Usually, 3D printer manufacturers offer talks, conferences, and workshops in schools and universities to let people know about this technology. 3D printer manufacturers have active Facebook fan pages and blogs where people write their comments and share their ideas, which help them to *build a virtual community* of technology enthusiasts. John S. explains:

[6] Remote support and online meeting software.

"On our website we have a blog, we have videos, also a YouTube channel; and we share some of the knowledge that we are acquiring."

Although at low levels, 3D printer manufacturers may also ***capture value*** by generating *customer loyalty* and *more sales* via 3D printer kits and workshops. One of the firms not only sells the fully assembled 3D printers, but its star product is a 3D printer kit that people have to assemble themselves. According to Charles "[people] have a sense of self-realization when they make a technology that everyone would consider complex.

The influence of 3DP on 3D printer manufacturers' ***value distribution*** is limited. Usually, they sell their products directly to the customer and do not use intermediaries.

Table 5. How 3DP is Influencing Manufacturers of 3D Printers

Quotation	First order concepts	Business model components
"We have been working in the drones sector [and] possibly in other sectors. We plan to work with robotics in the near term." (Carlos)	Flexibility	**Value creation**
"Yes, … [we also develop technology] … A couple of months ago, with Luis Cárdenas … He developed a mechanic spider to be paired with a smartphone by using the Theo Jansen mechanism. All that with the aim of creating a workshop. And Camilo was working on a robotic arm that was developed here, at the makerspace." (Andrés, from a makerspace) "We use laser cutting … and other classic shop tools such as drills, cutters, and others. And we develop 3D printers, CNCs [Computer Numerical Control machines], and drones." (Carlos)	Core competences: technology development	

"The fact that you do not have to create a mold to make something custom represents a very high gain" (Carlos) "Recently we are developing a drone … this is the first drone we are doing by ourselves. We are doing here some pieces of the engine with highly resistant components." (Andrés)	Product offering: new technology	**Value proposition**
"I see the option to promote [3D printing] development in Colombia and in Latin America through education." (Carlos)	Service Offering: Education and Training	
"Companies need [a prototype] that is cheaper, faster, and that looks like an end-product. 3D printing is a tool that gives you that." (Carlos)	Service Offering: Product Development	
"Our added value is to have a close relationship with customers and to produce perfect prototypes because we do the post-production process pretty well and because we are aware of the customer needs. We are in constant communication with the customer because this is a matter of design; … Sometimes people change their ideas a lot and want perfect prototypes." (Juan Sebastian) "I believe that our relationship [with the customer] is extremely close. Because I am in charge of the whole area, I have costant contact with them. I look after their requests very quickly because we … want to generate good word-of-mouth reputation." (Andrés)	Close relationship with customers	**Value communication**

"In our website we have a blog, we have videos, also a YouTube channel; and we share some of the knowledge that we are acquiring." (Juan Sebastian) "We treat our customers very well... we want them to leave with a very good image of the space. More than the space, it is the people who give it life. That's what we want, we try to meet their needs quickly to continue making our contents, developments, and research." (Andrés)	Community building	
"We have the memberships that every Makespace must have... It is a coworking space, ... people can come here and work on the machines directly. That is a way to monetize the space." (Andrés) "Our model is this: sell the machines through workshops or through kits. And eventually, have a recurrence of purchases through the sale of raw material—customer loyalty." (Carlos)	Revenue model: customer loyalty	**Value capture**
No influence reported		**Value delivery**

1.4.2. Influence of 3DP on Existing Business Models

1.4.2.1. Industries that use 3DP for in-house tooling and prototyping

One of the 25 firms analyzed uses 3DP to build prototypes before starting mass production. The core business of firms that use 3DP for in-house prototyping is not based on 3DP; for them3DP is just a tool, like many others, that complements the firm's set of technological resources. Consequently, *the influence of 3DP is limited only to a few elements of the value proposition, value creation, and value communication* (Table 6).

A company that manufactures plastic packaging for the beverage, pharmaceutical, and personal-care industry, uses 3DP in the product development process to make prototypes that were previously made by using traditional prototyping processes. 3DP has affected ***value creation*** of this company because *prototyping time is reduced.* William, from the product development area of this firm, explains that it now takes less time to produce a prototype: "Let's say it takes a full day [to produce a prototype], and it depends on the size and complexity of the part to be produced ... on 3DP it can be done in six hours." Even if making a 3D printed prototype is not cheap because of the resin[7] cost, the *total cost of producing a prototype is also being reduced* and the quality increases. According to William "[making a prototype in the past] cost 25% more. Moreover, before, it took longer and there were more people involved in the process ... Those prototypes were solid...not empty. They were very heavy." *Producing a 3D printed prototype requires fewer people and processes*: "These [traditional process] prototypes usually start from the 3D model design process; then, they go to the numerical control process to be programed and then placed in the CNC machine ... which is a longer process. But now, you [can] handle this directly from the design area, where we develop the model, and right after, if we need it, we send it to printing." (William)

3DP has also influenced ***value proposition*** because it allows offering the *possibility to see, test, and modify prototypes before mass production, which may save customers' time and money.* According to William "Customers have the opportunity to see, touch, and test a prototype... Many customers just want to touch it, see it, and things like that. There are other customers who use it within their production plants to check what changes are needed on the prototype or if it works properly: they check if the prototype height is right, if the width is right ... then it is easier to make changes quickly." He adds, "When prototypes are delivered, companies perform functional testing; they test

[7] Polymers used by the 3D printer to print an object.

how to assemble the product on the conveyor belt, they implement ergonomic tests, transportation tests, and verify how the product will behave on the conveyor belt." William explains that 3DP has helped them to *offer a more integrated service*: "Customers know that we have [3DP] and they like it. Then, they may prefer us…because they know that we have the advantage of being able to show the product as it will be."

3DP has also influenced the company's ***value communication*** because it allows it to communicate with customers through a real prototype of the product they are going to buy, which may help to *convince them to buy, and hence increase sales*. Kristina, from the plastic packaging company, claims that "3DP is a tool to reach new customers. To generate new sales … [3DP has influenced] the marketing and commercial areas of the company because they have contact with customers and they are the ones who can come up with something more distinctive and compelling."

Table 6. How 3DP is Influencing In-house Prototyping

Quotation	First order concepts	Business model components
"Many times we have to evaluate the threads we produce, the precision of the plastic caps … to check if they match, before sending them to the customers." (Camilo)	Product evaluation	Value creation
"Before, there was the designer who designed the packaging; a subsequent programming process … then, another person on the CNC adjusting the programs to make the prototype; then, making the prototype; then, many times, glue the pieces to each other, make some lateral cuts to glue the pieces, and form the figure; and then polish the figure." (Neil)	Time and costs savings	

"The machine is [printing] and we are not employing a person dedicated to making it … [Before], there were one or two people dedicated to making a prototype. Now, you simply press the printing button and keep working on something else … and in a while, the machine ends the printing process … you take the prototype out of the machine, and it is ready. But you do not need to have someone tending the prototyping." (Tatiana)	Fewer people and processes	
"The great advantage that we have seen [with 3DP] is that we can show to our customers the products they selected before starting mass production." (Camilo).	Service offering: Fast prototyping	**Value proposition**
"The customers really want to know how the product is and how it will be. Then one sends them a prototype and then they can touch it … it is not like seeing it on the computer." (Camilo)	Testing	
"I think [customers] see that we offer a more comprehensive service … here, we cover the whole process: we do product design, we do prototyping, and we make mold design, manufacturing, injection molding, or the process they will use to make the article." (Camilo)	Comprehensive Service	
"We can impact a customer more directly. The process of submitting a proposal does not take two or three months while we develop a mold. [By using 3DP] we can show a very real prototype, similar to what they expect to have, without waiting to have a mold." (Camilo) "I see [3DP] as a tool to reach new customers, to generate new sales." (Tatiana)	Display products	**Value communication**
No influence reported		**Value capture**

No influence reported	**Value delivery**

1.4.2.2. Providers of 3DP Services and Product Developers

These two groups of companies have been influenced by 3DP in a similar way (Table 7). *3DP services providers' main offerings* are the design (or modification), printing, and scanning of models or prototypes. The *developers* go beyond these services and provide to customers the advice and technology to design, print, test, manufacture functional models, and mass-produce end-products. Some developers even help launching products to the market.

Judging from our sample, it seems that 3DP has influenced the value creation, proposition, and communication of developers and 3DP services providers, while their value distribution and capture have not been affected. Developers and 3DP services providers report that additive manufacturing is affecting ***value creation*** because it has *reduced the complexity of their product manufacturing*; a 3D printer may print almost any model scanned or designed on a computer in only one process and using only one machine, which in many cases was not possible before. Moreover, with 3DP, *developers and 3DP services providers spend less time and money to offer their products and services, and have more flexibility* – with the same machine it is possible to print a wide range of products to satisfy the needs of several market segments.

As with 3D printer manufacturers, 3DP has also affected the ***value proposition*** of 3DP services providers and developers because *3DP has increased their service and product offerings*. Currently, they can offer their customers *cheaper, faster, and better-quality prototyping and product development:* "3D technologies reduce time and costs …3D printing has improved greatly. It offers precision and very good quality" (Francis, from a company that provides 3DP services). This may bring two gains for customers: *a rise in the frequency of new product launches and the use of printed prototypes with* *marketing purposes*. For example, a product developer reported that one of his customers, a company that designs and builds production factories, previously showed their customers digital and 3D versions of the plants they design, but now this company shows the printed prototype of their plants, which catches the attention of potential buyers and puts them in a competitively advantageous position in relation to competitors that still use traditional computer design to show their products.

3DP has affected the ***value communication*** of developers and 3DP services providers to a lesser extent. They report having *long-term and continuous interactions with customers*, who in many cases do not know the advantages and limitations of this technology, and consequently need more advice and support in the development of their own creations: "The strategy is to give [customers] good advice… The customer calls us, we check the files together, and we have a conversation about what is really going to work best at the material level, at the detail level, and at the process level." (George, product developer).

Table 7. How 3DP is Influencing Providers of 3DP Services

Quotation	First order concepts	Business model components
"3DP has a very big impact on how products are designed and developed." (Robin)	Product design	Value creation
"3DP eases and speeds prototyping. Companies reduce their product development times." (Robin)	Time savings	
"3DP technologies reduce costs… It is not the same to manufacture a mechanized prototype - which can cost 30.000.000 Colombian pesos - than to print it - which can cost from 600,000 to 1.000.000 Colombian pesos." (Oscar)	Costs savings	

"The number of errors and reprocesses in making products have been reduced." (Robin)	Less errors	
"Since it is possible to develop ideas more economically, it is possible to be more innovative and creative … [3DP] allows developing different types of garment… There are flexible materials that allow developing dresses, underwear, accessories." (Tom)	Innovation	
"3D printers are very helpful for development and design companies. Due to 3DP these companies have a better performance because it allows a faster design." (Robin)	Service offering: Better performance	**Value proposition**
"It is super interesting to see how [engineers] fulfill their dreams, as they see their imagination come true due to 3DP." (Kevin) "People pay for something that is getting physical … when you deliver something physical, people are more motivated to request the 3DP service." (Theo)	Materialization	
"Clients often do not feel satisfied with just a drawing, they need a sample to be able to close a deal." (Robin) "My interactions with clients were looking at a screen, looking at a 3D model; there was little to talk about. Now the conversations with the clients are with a prototype in hand, not with a computer. The conversation is more fluid and interesting because you are already in the product you are not in the computer. The conversation moved from the computer to the product." (Robin)	Easier interactions	**Value communication**

"A printed model can speak for me and that I do not have to talk. A model can say everything by itself." (Ronny)		
"There are clients that tell me to design a product, but I can also manufacture it, which allows me to generate extra incomes." (Theo)	Complementarity	**Value capture**
"Our most profitable service is the manufacture of 3D prototypes and the small-batch production." (Robin)	Rentability	
"I do not have the opportunity to deliver the products, it's almost always the client who comes." (Theo)		**Value delivery**

1.4.2.3. Distributors of 3DP Technologies

Since the core business of this group of companies is generally limited to the commercialization of 3D printers, it is quite obvious that 3DP has a limited influence on them. However, 3DP has allowed distributors to increase their product offerings and technical services ***(value proposition)*** and strengthen their relationship with customers ***(value communication)***. James, from a 3D printer distribution company, describes the situation: "We focus our value proposition not on the sale of equipment but on the post-sales support ... in recent years we have focused on strengthening our technical support and warranty ... we offer four hours of personalized training with an expert, we connect with the customer by Skype, and we teach him how to use the equipment."

1.5. Conceptual Model

1.5.1. Technology and Business Complementarity

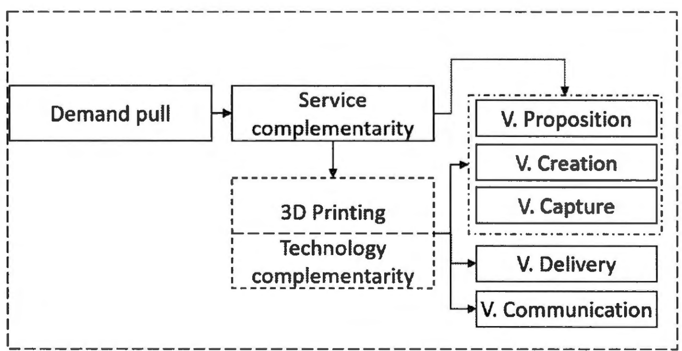
From the interviews, two notions emerged related to the firm's capacity to increase its value proposition to customers. The first regards the right mix of technologies an enterprise should have to increase its value proposition, which is a kind of *technological complementarity.* In the case of some developers and printers who started just with 3D printers, they soon realized that this technology was not enough to have a profitable business, consequently they bought 3D modeling software, 3D scanners, and other product development and manufacturing technologies that complemented 3DP. Technology complementarity has several features: it helps to improve the quality of services and products offered, it facilitates manufacturing processes, and it increases enterprise flexibility. Technology complementarity emerges from the need to increase service offering. Arthur, from a product development company, explains: "In addition to 3D printers, we have incorporated optical metrology and 3D software, with these technologies we help companies to develop their products from scratch."

The second notion, *service complementarity,* is related to the new services that complement a firm's existing services to increase the value proposition of the whole business, attract more customers, and make the firm more profitable. Almost all the informants reported that technology and service complementarity was essential to strengthen their business model. For Jean, from a product development company, "A resins and molds service was complementary [to 3DP] … The resins help customers who came to make a prototype and sought the next step that was making the mold of those pieces. We realized that it was important and then we decided to buy the machines to provide this additional service."

Most of the times complementary technologies allow complementary services, which attract more customers and increase the perceived value that customers have of the company. These complementarities may improve the value proposition (by offering more services, by bundling them and by increasing the synergies between services and shared resources) in important ways. Moreover, they may give access to new market segments, and be a source of differentiation and diversification. Such service complementarities are not always planned beforehand. They emerge from changing customer's needs, they evolve as complementary technologies advance, and they may lead to the elimination of less profitable services. Technology and service complementarities seem to influence mainly developers and printers, and to a lesser extent 3D printer manufacturers, end-product manufacturers, and industries that use 3DP for in-house prototyping.

Often, service and technology complementarities are not planned in the initial value creation (technology and assets) and value proposition (product-service offering). Rather, they are added later in response to demand requests for such services or as the technology evolves to enable them and justify them (Figure 4).

Figure 4. Technology and Service Complementarity



1.5.2. 3DP and Business Models

3DP seems to influence business models (Figure 5) and foster the development of new enterprises. The most important 3DP influence is on value proposition and value creation. 3DP helps to increase product and service offering, allow high levels of customization, and allow customers to materialize their developments cheaper, faster and with greater quality. Moreover, it introduces a novelty factor that also attracts customers, which use this technology in creative ways. 3DP also reduces prototyping complexity and in some cases mass-production complexity, allows flexibility, and also reduces time and production cost. Sometimes it is hard to draw the line regarding the impacts of 3DP on value creation and value proposition because they are very tied; a new technology or process may add value within the firms well before it translates into a better value proposition for customers. In many cases changes in value creation precede changes in value proposition; in other cases this does not happen and value proposition remains virtually unchanged.

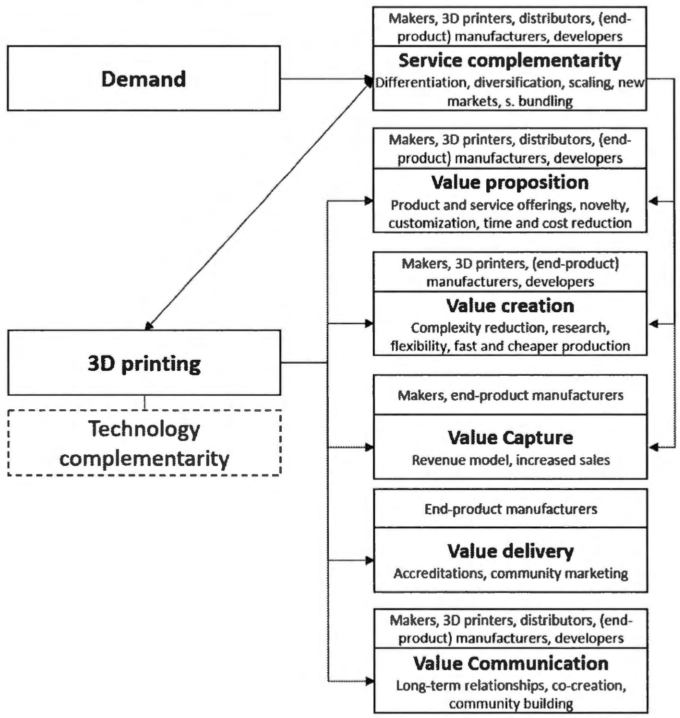
3DP also affects the value communication of all six types of enterprises analyzed. This technology induces enterprises to have a tighter relationship with customers, a more frequent and fine-grained dialog with them, and long-term technical support and guarantee that maintain the provider-customer relationship.

In other enterprises, such as end-product manufacturers, the impact of 3DP on value communication and value delivery is even greater. These enterprises have an even stronger relationship with customers since they have to build a community to co-create their products with their customers, interchange knowledge at a higher level, and interact with the customers of their customers.

3DP impacts the value capture of 3D printer manufacturers and end-product manufacturers, but indirectly (via value creation or proposition) and in a lower extent. They report that 3DP allows them to bundle services and products, and have enough flexibility to couple existing services with more services to increase revenues.

Complementary technologies can easily couple with 3DP to enhance service complementarity. Customers' demands and to a lesser extent strategy and technology advances play an important role in the development of complementary services enabled by 3DP, and complementary technologies. This complementarity seems to increase customers' perceived worth toward the enterprises.

Figure 5. 3DP and Business Models



1.6. Conclusions

Through the exploration of 25 case studies, the results suggest that 3DP may not only be influencing firms' value creation (internally) for the firm and value proposition (externally) for the customer; it may also influence value communication and distribution to a greater extent than reported in previous studies. The impact on value capture, however, seems to be indirect – through value creation – and minimal. As reported by informants, 3DP is leading to the development of new business and business models, and is also affecting existing business. 3DP allows the creation of services, and products that were not possible before – or that were developed in a very different fashion.

Companies that manufacture, use, or commercialize this technology are being affected differently. Manufacturers of 3DP have a new value proposition to their customers: a new technology that people can use to materialize their own creations. Moreover, they have a tool that strengthens their value creation: a machine that allows them to create new products or improve existing ones at a lower cost and faster than before.

From the data analysis emerges that 3DP may also be influencing the value proposition, value creation, and value communication of providers of 3DP services and product developers. Regarding the value creation and proposition, 3DP has increased the offering and quality of products and services they offer, reduced the complexity to manufacture certain prototypes and models, increased manufacture flexibility, and reduced costs and time in the prototyping process. With 3DP, printing services providers and product developers are forced to hold a more frequent and long-term dialog and interaction with customers (value communication), who still have many doubts about how this technology works and its capabilities. Manufacturers of end-products have been the most influenced by 3DP. In addition to the effects that 3DP has had on product developers and 3DP services providers, 3DP has affected their managerial, commercial, planning, and production processes.

It seems that the industries that use 3DP for in-house tooling have also been affected by 3DP. The value creation and proposition was affected because they now can offer the customer the possibility to see, test, and modify their prototypes before mass production; moreover, they now offer a more integrated service. Moreover, prototyping time and cost is being reduced, fewer people and activities are involved in the process, and the prototype quality increased. The value communication has been influenced because a prototype printed on a 3DP help the commercial area to increase the sales.

One of the main 3DP contributions is that product development processes are cheaper, faster, and more sustainable, because there is almost no material waste when printing a piece. However, a faster and cheaper prototyping may allow enterprises to launch products faster, which may also cause that current products become obsolete sooner, which may translate in more waste and overconsumption.

While 3DP benefits new firms, it also undermines the viability of existing ones. Enterprises of artisans and artists who make prototypes by hand, jewelers who manufacture jewelry molds, and architects who offer mock-up manufacture services, just to name a few examples, are probably at risk in the short term. During the interviews, I heard several cases of companies that are printing spare parts they previously purchased from their providers. This may generate intellectual property problems and patent or copying infringement.

It seems that one of the main 3DP contributions is that product development processes are cheaper, faster, and greener, because there is almost no waste when printing a product. However, faster and cheaper prototyping may allow enterprises to launch products faster, which may also cause current products to become obsolete sooner.

In the 3DP sector, technology acquisition is not just an issue of strategy or business opportunity. Several of the smaller companies interviewed obtained their first 3D printers mostly because of the novelty factor – the technology was new and *cool*. With time, they realized they could monetize these printers. Some interviewees/firms never envisioned launching a company with several employees and offering so many services.

This study has several shortcomings of which three require special attention. First, since the research was based on only 25 cases, one should be careful in extrapolating from these results. The author tried to provide some details about the cases analyzed, which should help the reader to contextualize the results. Second, since the sample was limited, it will be necessary to do further research on how 3DP affects other enterprise types differently from the ones analyzed in this work. Third, the sample involves enterprises from only one country, and factors specific to each country may also affect the degree of influence that 3DP has on a business. Further research is needed to overcome these limitations by increasing the sample size and by developing cross-sectional analyses in different countries. Future research should focus on managerial practices, strategies, and organizational changes needed to reap more benefits from 3DP and other Industry 4.0 technologies.

2. CHAPTER II: MICROFACTORIES AND THE NEW ECONOMIES OF SCALE AND SCOPE

Abstract: This paper explores the microfactory model, the elements that enable it and its implications. We argue that microfactories reduce the risks and costs of innovation and that they can move various industries toward more local, adaptive and sustainable business ecosystems. This conceptual paper explores several processes and practices that are relatively new; hence, it uses online secondary sources (e.g., interviews with CEOs, videos, blogs and trade magazine articles) extensively. Given its versatility and high automation levels, the microfactory model can fill the gap between artisanal and mass production processes, boost the rate of innovation, and enable local on-demand fabrication of customized products. Currently, manufacturers generally need to make large investments when launching a new product, despite high uncertainty about customer acceptance, thus risking considerable losses. The microfactory model offers a safer alternative by allowing a firm to develop and fabricate new products and test their acceptance in a local market before mass producing them. Microfactories also enable the local on-demand fabrication of highly customized products. This article contributes to the discussion of the economic advantages and disadvantages of scale and scope, which have been insufficiently explored in the digital domain.

*Keywords***:** Microfactory, digital economies of scale and scope, digital manufacturing, crowdsourcing, crowdfunding, 3D printing, local on-demand fabrication.

2.1. Introduction

Manufacturing technologies, production processes and business models have changed significantly in recent years. Advanced technologies today are more interconnected, “smart”, flexible and pervasive (Stephen, 2014). Production processes are faster and more efficient (Ghobakhloo, 2018). And some business models have become leaner by tightly integrating several functions while using crowdsourcing and crowdfunding to be more innovative and agile. Many of these changes converge, most notably, in the microfactory (MF) model. Initially, MFs were defined as small-scale facilities that combine production and retailing functions in a single site serving local or regional markets (Wells and Orsato, 2005). We update this definition and consider MFs as fabrication units optimized for the small-to-medium-scale manufacture of a variety of products by heavily using digital manufacturing technologies. In this paper, digital manufacturing refers to the integration of computer-based capture, simulation, visualization, prototyping, fabrication and data analysis tools to create and reproduce a product. This paper argues that MFs allows the efficient customization of products and can bridge the enormous gap between artisanal production (i.e., custom goods produced in low quantities) and mass production (i.e., standardized goods produced in large quantities). In other words, MFs can help colonize the current ‘no man’s land’ between artisanal and mass production (J. Rogers, 2014) by enabling the gradual scaling of manufacturing beyond a few exploratory prototypes and toward the efficient fabrication of hundreds, rather than millions, of units per year. Thus, with MFs it becomes possible to develop, produce and test new products faster and more cheaply, facilitating a smooth and low-risk transition from low to large production runs. Currently, manufacturers are often forced to make large investments when launching a new product despite a high uncertainty about customer acceptance, thus risking huge losses. MFs offer a safer alternative by allowing innovative firms to develop, fabricate and test new products in local markets before mass producing them.

This paper addresses the question: *What are the implications of MFs for the economies of scale and scope of an industrial sector?* It explores the MF model, the elements that enable it and its likely implications for the evolution of industrial ecosystems. Since some of the concepts explored here are new and rapidly evolving, we use online secondary sources complemented with academic sources. For the academic sources, we used the keywords "microfactory", "micro-factory" and related terms (in article title, abstract, keywords; all years; article). For the non-academic sources, we used similar keywords in the Google search engine. This allowed us to access interviews with CEOs, videos, blogs and trade magazines discussing MFs. We used investigator and data triangulation (Patton, 2002) to increase the consistency and impartiality of our analysis. The review of online sources helped us to assess how current MFs work and to conclude that MFs are more dynamic and diverse than is stated in the academic literature. In our analysis, we looked for patterns that repeated across sectors and across various types of MFs. Although the MF model can be applied to a large variety of industries, here we only describe some MFs in the automobile, home appliance, and shoe manufacturing industries.

Some authors use the term 'micro-fabrication' to refer to the manufacture of sub-millimeter or even nano-scale objects using small, modular, and efficient machines (Gaugel & Dobler, 2001; Mishima, 2006; Zhakypov et al., 2017) or the miniaturization of the production system to match the size of the object produced (Yamanaka, 2006). In this paper, alternatively, a 'microfactory' refers to any fabrication unit optimized for the small-to-medium-scale manufacture of a variety of products.

There is abundant literature on the economies of scale and scope for manufacturing physical products. Haldi and Whitcomb (1967), Panzar and Willig (1981), Chandler (1990) and others have explored this field. However, the literature on digital products and on networked physical products that heavily integrate software, data and alternative sourcing and funding approaches, is much less extensive. With the development of digital platforms and digital technologies, MFs have much evolved since the concept was introduced back around 1990. They are increasingly automated and have diversified well beyond the car manufacturing industry (Wells and Orsato, 2005).

This article tries to advance the conversation about MFs in three ways. First, it highlights some features not discussed in prior scholarly literature on MFs (e.g., their rising degree of automation and their frequent recourse to the crowdsourcing and crowdfunding of innovative projects). Prior MFs studies have mostly provided an industrial ecology perspective. Such was the case of Wells and Orsato (2005) and Williams (2006), who advanced the concept of microfactory retailing as a more ecological alternative for the automobile industry. Second, this article provides an in-depth analysis of how various digital manufacturing technologies can converge to change the way products are conceived, funded, designed, tested, and made. These changes offer new and more efficient manufacturing options that could bridge the current gap between artisanal and mass production regimes. Third, this article expands the scholarly discussion on digital economies of scale and scope. Progress in 3DP, artificial intelligence, the Internet of things and other emerging technologies enable radically new production and logistics solutions. Scale and scope theories need to be updated to reflect these new realities.

2.2. Theoretical Foundations

2.2.1. Scale Economies and Diseconomies

Economies of scale exist when per-unit average production costs decrease with output (Seth, 1990). Such economies result from spreading fixed costs over an ever-growing output volume (Besanko, Dranove, Shanley, & Schaefer, 2013). However, at a certain point, *average costs* reach a minimum level and then start to rise, generating diseconomies of scale. Diseconomies of scale emerge because as firms grow, labor costs may rise, information flows may become slower and less reliable, and expansion may overburden managerial and other specialized resources. As a result, growing firms may become less adept at evolving optimally in response to changes in their business ecosystems.

According to Cairncross (1966) and Lipsey and Chrystal (2015), we need to differentiate between internal and external economies of scale. Internal economies of scale result from a firm's increase in its output, independently of other firms' actions. Efficient mass-production methods and a well-managed internal supply chain are key to such economies. External economies of scale emerge when increasing output by one firm augments the output and lowers the per-unit costs of other firms along a shared value chain.

Scale and specialization are related. In the words of Adam Smith, "The division of labor is limited by the extent of the market" (Smith, 1776, p. 31). Firms tend to specialize when demand levels for their services are high enough to recover the upfront time and money invested to acquire specific skills and equipment. In other words, realizing scale economies requires sufficient throughput. Thus, larger markets may support a more diverse set of narrow specialties.

But there are also scale diseconomies. Despite the prominence of approaches such as just-in-time and lean manufacturing, firms seeking economies of scale require large, task-specific capital investments and may, as a result, become inflexible. The inflexibility of large-scale manufacturing hampers the adjustment of output to demand, and the rapid switching from one product to another. Hence, responding to market fluctuations and to entirely new opportunities becomes difficult with conventional fabrication technologies and organizational practices. Moreover, some firms may face high manufacturing break-even points (e.g., where plants must run at a minimum of

85% capacity to be profitable), which may result in oversupply. Overall, seeking high economies of scale makes sense only when demand is predictably high and stable (Wells & Orsato, 2005). But even then, a switch to mass production can be a high-stakes and risky move. Running a plant at less-than-full capacity is costly, but such costs pale in comparison with those of sudden plant obsolescence or the inability to match the cost reductions of larger competitors. Eventually, flexible fabrication technologies should help minimize such enormous risks. But for the time being, as Apple, Nike and other fabless giants have shown, subcontracted fabrication often is the safest route for the innovative firm.

2.2.2. Economies of Scope

According to Panzar and Willig (1981, p. 268), "There are economies of scope where it is less costly to combine two or more product lines in one firm than to produce them separately." And according to Besanko et al. (2013), costs can decrease with increasing product and service variety for several reasons. First, because fixed costs do not increase proportionally with production variety. In a factory, it is often possible to install a new assembly line for a new product and benefit from existing equipment and facilities while reducing the average cost per unit. Second, because variable costs can also be reduced. Employees can share knowledge and experience in a wider range of goods, and staff can manage a broader product portfolio. This product diversity may generate synergies beyond those enjoyed within a single product line. Brynjolfsson and Milgrom (2013) use the term *complementarities* to describe organizational practices that have an enhanced combined effect. Complementarities are better known in the strategy literature as *strategic fit*, which refers to how firms match and leverage their core capabilities and operations to increase competitive advantage and minimize the risk of imitation (Porter, 1996).

2.2.3. How Digital Technologies can Impact Scale and Scope

In the past two-hundred years, scale and scope have become increasingly orthogonal in the business world, as artisanal and industrial regimes have diverged. Two consequences of this divergence have shackled innovators: the inability to gradually scale up the deployment of new products and the inability to supply customized products at affordable prices. Fortunately, as it is discussed in the next paragraph, digital technologies are rapidly changing that, by enhancing the level of automation while reducing waste and pollution at all scales.

Digital technologies may affect production scaling in several ways. First, they can increase manufacturing efficiency, by allowing faster, more precise and lower-waste continuous production. General Electric, for example, has combined several advanced digital technologies to create the Brilliant Factory (Stearns, 2017). This solution involves using radio-frequency identification (RFID) tags, sensors and smart glasses to track subassemblies and monitor operations, which helps optimize production, maximize asset usage and improve product quality. Second, they can provide timely and pertinent data that, combined with different techniques (e.g., lean manufacturing), ensure operational excellence (General Electric, 2016). General Electric is also connecting machines and digitizing manufacturing to obtain a continuous data flow that helps them to make opportune and informed decisions, guide operations in real time and avoid costly mistakes. Third, digital technologies may help to virtually simulate or model future scenarios that lead to better production processes (Scheel, Monahan, Eitelwein, & Koelbli, 2015). By combining digital technologies and traditional techniques such as lean manufacturing – a process called digital lean – firms can leverage sophisticated statistical assessment, big data and neural networks to increase predictive capabilities, identify potential problems before they occur and conduct flexible simulations. Fourth, digital technologies may better connect production to potential sales (Kautzsch, 2016). A better demand forecast favors more accurate feedback between design, production and sales. It allows manufacturing products more suited to market needs, which may result in larger sales and less inventory. Finally, embedding digital technologies into operations may improve equipment maintenance and performance (Kautzsch, 2016). Consequently, factories may run more smoothly and with fewer unplanned stops, as well as less energy and raw material consumption.

Digital platforms are key for industrial scaling; they use digital technologies to create scalable and flexible business models by connecting people, organizations and resources in a multisided ecosystem in which high amounts of value can be created and exchanged. Platform-based firms often outcompete traditional firms by employing only a tiny fraction of their employees and infrastructure and by evolving very rapidly their business models (Parker, Alstyne, & Choudary, 2016; Simon, 2013).

Digital manufacturing not only facilitates rapid upscaling, technologies such as 3DP also enable product variety (i.e., a diverse product line), which in turn offers three main benefits. First, scope economies, resulting from costs shared among different products (important in distribution, but less so in creation and fabrication until the arrival of 3DP). Second, portfolio effects, resulting from weak (additive) complementarities, very useful if the demand for such products is uncertain or cyclical. And third, synergies resulting from strong (supra-additive) complementarities, often crucial at the R&D stage. It is now possible to connect any number of 3D printers to reach medium production volumes while maintaining high product variety. Switching products is becoming faster and cheaper, thus augmenting flexibility and scope advantages.

But perhaps the most unexpected and transformative impact of digital technologies has been in bringing automation to the low-productivity, small-scale world of artisans. Arguably, our growing ability to gradually scale up the deployment of new products and to supply customized products at affordable prices is best exemplified by the current rise of highly automated microfactories.

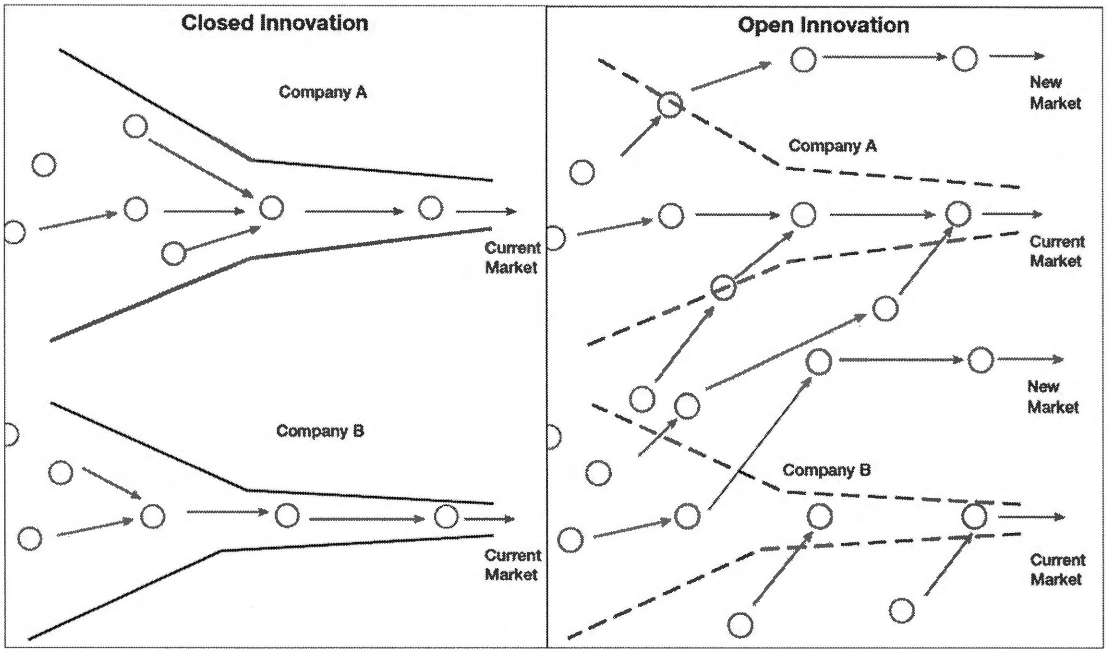
2.2.4. Open Innovation and Users' Innovation

2.2.4.1. Chesbrough's Closed and Open Innovation

According to Chesbrough (2003), there are two paradigms of innovation: *closed* and *open* (Figure 6). The closed, traditional, paradigm is inwardly focused and was widespread during the early twentieth century. In this paradigm "all these activities are conducted within the firm. There is no other path for ideas to come into the firm, nor is there any other path for products and services to leave the firm. This tight coupling also assumes no leakage out of the system." (Chesbrough, 2003, p. 30) In closed innovation, R&D activities are developed within the firm, which leads internally developed products that are then distributed by the firm itself (Chesbrough, 2005).

For Chesbrough (2003), in the open innovation paradigm "ideas can come from inside or outside the company and can go to market from inside or outside the company as well" (p. 43). In this paradigm, firms incorporate external ideas and use external paths to market. Companies know that ideas abound in the environment; hence, they try to use them to create value, while they develop business models to capture some of this value. Chesbrough (2005, p. 2) defines open innovation as "the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively."

Figure 6. Knowledge Landscape in the Closed and Open Innovation Paradigms



Source: Chesbrough (2003)

2.2.4.2. Von Hippel's Users' Innovation

According to Von Hippel (2005), innovation can be *manufacturer-centric* or *user-centered.* In the manufacturer centric approach products and services are developed by firms in a closed way; products are protected with patents and copyrights to prevent imitation. In this traditional approach, users do not have a role in developing new products; instead, they are passive agents with needs that are identified and satisfied by firms via new or improved products and services. In the user-centered innovation process, innovation is democratized; users (firms or individuals) of products and services propose and implement innovations. Moreover, they can benefit from the innovations developed and deployed by other users. Advances on online platforms and digital technologies have facilitated user-centered innovation. Now it is easier to develop or improve new physical or virtual products, deploy their progress online, and get faster feedback.

2.3. Microfactories

2.3.1. Previous Research on Microfactories

A few studies have addressed the issue of MFs. From a sustainability perspective, Wells and Nieuwenhuis (2011) and Wells and Orsato (2005) explore MFs as potential enablers of more localized production. These authors argued that the automotive sector was ready for change and that MFs could be used to improve it, since they require less initial investment, recombine functions currently dispersed, reduce economic and environmental transport costs and revitalize the local economy. In the same vein, Williams (2006) argued that MFs could make the car industry more sustainable through smaller plant sizes, more innovative vehicle designs and better relationships with customers. More recently, Basmer et al. (2015) conclude that bottom-up collaboration (e.g., as in Fab Labs) and new manufacturing technologies offer better chances of greater social sustainability in manufacturing. In a very different context, Wilson and Lumkes (2015) explore the use of MFs to manufacture low-cost agricultural utility vehicles in sub-Saharan Africa for local markets. They conclude that MFs could profitably manufacture vehicles adapted to local conditions by using locally sourced parts, and they argue that this model can be also used in other regions of sub-Saharan Africa.

All the papers reviewed above have focused mainly on the car manufacturing industry and have addressed the issue of MFs mainly from the perspective of a more sustainable and local industrial ecology. In so doing, they have tended to overlook aspects related to the risks and costs of innovation and to the use of alternative sources of funding and ideas, aspects that are at the core of this paper.

Other authors (Gaugel & Dobler, 2001; Mishima, 2006; Yamanaka, 2006; Zhakypov et al., 2017) have also studied optimization issues and applications of MFs, but their notion of a MF is very different from ours. For these authors a MF allows the manufacture of sub-millimeter or nano-scale objects using small modular machines, or the miniaturization of the production system to match the size of the object produced. We have consequently chosen not to review their work here.

2.3.2. The Recent Rise of Microfactories

Most production systems are based either on small workshops with artisanal, labor-intensive processes and low output levels, or on large factories with standardized, capital-intensive processes and high output levels. This dichotomy leaves a large gap between very low production volumes (dozens or hundreds of units) and very high production volumes (millions of units). By leveraging on-demand digital manufacturing, often coupled with crowdsourcing and crowdfunding, MFs offer a viable alternative between artisanal and mass production. Besides allowing firms to produce small production runs, reduce production costs and time, and increase product variety (Table 8), MFs may also let small and large companies run exploratory production batches before investing millions of dollars in new products with uncertain demand. In other words, MFs can reduce the risk of innovation by facilitating the gradual scaling up of production volumes as demand uncertainty falls.

Table 8. Mass Production vs. Microfactories

Mass Fabrication	Microfactories
Very high production volumes (1M+ per year)	Low and medium production volumes (100 to 10 000 units per year)
Global value chains	Local value chains
Homogeneous products and scale economies	Heterogeneous products and scope economies
Strong protection of intellectual property	Weaker protection of intellectual property
Relatively low innovation rates	High innovation rates

Several companies and production units fit into the MF model: Local Motors Industries (LM), Divergent 3D and the Wikispeed project in the car manufacturing industry, Haier's FirstBuild in the home appliances manufacturing, GE's Fuse in the industrial products manufacturing, and Adidas Speedfactory in the shoe manufacturing industry, among others. Instead of big facilities for high-volume manufacturing, LM has four microfactories (Knoxville, Chandler, National Harbor and Tempe) of around 20,000 to 40,000 square feet employing about 160 people to run low-to-medium production volumes and serve local and regional markets (Local Motors, 2018). These MFs allow LM to have a more direct contact with customers, to adjust its products to local needs more easily, and to reduce shipping and storage costs, and thus its working capital needs. LM also uses its crowdsourcing platform (Launch Forth) to leverage the creativity of a large online community of designers and engineers (around 52,000 members) to brainstorm, prototype, test and launch products, using 3DP as a core element. Hence, LM reduces design-to-market times, design costs and waste. This company is currently using additive technologies for the on-demand manufacture of Olli, an autonomous electric shuttle, reducing tooling costs by 50% and overall production time by 90% (MakerBot, 2018).

FirstBuild's microfactory employs 23 people and uses the latest manufacturing technology, crowdsourcing and crowdfunding to create and fabricate appliances in a way that reduces development time, costs and risks (Hagel, Brown, Wooll, & de Maar, 2018). This company uses crowdsourcing to receive direct product feedback from its 23,000 community members and employs crowdfunding to quickly forecast demand (customer receptivity) and to secure funding and sales before manufacturing. FirstBuild works by receiving ideas of sellable appliances from its members, the best ideas are refined by their peers (contributors) and then sent to design, prototyping and finally launched to the market (FirstBuild, 2018). The authors of the best ideas (concept leaders) and the key contributors receive financial rewards and royalties from the products sales and FirstBuild also secures a percentage of the earnings. The entire manufacturing process takes place in-house.

Adidas Speedfactories are innovative, highly digital and automated factories that allow the company to produce custom shoes in small batches by using 3DP. These microfactories aim to meet the needs of specific individuals, bring products to market faster, and react timely to customers' demands (Bain, 2018). The 49,000 and 74,000 square feet Speedfactories in Ansbach, Germany and Atlanta, Georgia with around 160 employers are significantly smaller than the large Asian factories with more than 500 employees in which most Adidas shoes are currently made (Bain, 2018; Beilin, 2017).

As the above examples indicate, there are at least two different types of MFs: those that are innovation-driven (e.g., Local Motors and FirstBuild) and those that are customization-driven (e.g., Adidas Speedfactories). Whereas innovation-driven MFs try to reduce the costs and risks of innovation by increasing the scalability of new product launches, customization-driven MFs seek instead to democratize product customization on an on-demand basis for local markets. Consequently, while innovation-driven MFs tend to be quite dependent on crowdsourcing and crowdfunding campaigns, customization-driven MFs are not.

Both types of MFs share some common elements and traits that distinguish them from conventional job shops. Due to their high reliance on 3DP technologies, MFs offer much lower setup costs and much greater flexibility than job shops. In addition, by vastly reducing the number of parts and by automating much of their fabrication, MFs are far less labor-intensive than job shops. As a result, whereas job shops specialize in particular processes, MFs can fabricate entire products and enable the shortening and relocation of entire supply chains closer to final markets. Finally, due to their reliance on virtual prototyping and 3D printing, MFs also produce much less waste than traditional job shops, which makes them more suitable for urban and suburban areas. These differences are starkest in the most local forms of on-demand fabrication. Small fabrication units in a space station, at the back of a shoe store or of a dental office are very close to the original Japanese notion of a desktop Microfactory (Tanaka et al., 2014), and have nothing in common with a job shop.

Microfactories can be part of small, standalone companies such as Local Motors, Divergent 3D and Wikispeed or belong to bigger companies such as Adidas' Speedfactory, Haier's FirstBuild and GE's Fuse. A MF usually has less than 50,000 square feet and between 4 and 25 employees.

MFs can play an enabling role in the overall trend toward a fully digital industrial ecosystem (often labeled 'Industry 4.0'). Most of them embody high levels of automation, virtualization, speed, connectivity and sustainability that are at the core of Industry 4.0. Since MFs need not require large setup investments, they can serve as pilot projects of larger and more ambitious Industry 4.0 initiatives.

While the likely impact of MFs on globalization is an open and complex question, we can surmise that they will help to boost the incipient trend toward the partial 'reshoring' of manufacturing -though perhaps not of jobs- back to the most advanced countries (De Backer, DeStefano, Menon, & Ran Suh, 2018). And while most MFs may gravitate to the vicinity of urban areas, some of them might also be suitable for sparsely populated rural areas.

2.3.3. Digital Technologies Converging on Microfactories

Digital sensing, simulation and fabrication play a central role in MFs. Such factories rely heavily on 3D printers, 3D scanners, laser cutters, computer numerical control (CNC) machines, computer-aided design (CAD) software and virtual prototyping.

These technologies plus connected sensors and controls, allow the networking of plants and facilitate agility, efficiency and modularity (C. Anderson, 2012).

2.3.3.1. 3D Printing

3DP, also called additive manufacturing (AM), is defined by ASTM (2013, p. 2) as "A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." Metals, polymers, ceramics, and even organic materials are used as feedstock (D. Chen et al., 2015; Lee, An, & Chua, 2017). 3DP allows low-cost customization, process flexibility and design complexity while reducing assembly work (Ian Gibson, 2017; Weller et al., 2015). Gao et al. (2015) and Steenhuis and Pretorius (2017) explore 3DP's status, challenges and implications, H. Rogers et al. (2016) describe and classify 3DP services, Chua, Wong, and Yeong (2017) presents standards, quality and measurement issues of 3DP, and Ian Gibson, Rosen, and Stucker (2015) describe a broad range of 3DP technologies.

To the extent that it can seamlessly fabricate complex components or products in one go, 3DP has the potential to eliminate dozens or hundreds of parts and their assembly, thus increasing the automation of entire value chains (Gershenfeld, 2012). Relativity, a start-up that aims to build rockets and launch satellites into space, is using 3DP to manufacture their rockets 10 times faster, 90% cheaper and with 100 times fewer parts than current industry practice (Relativity, 2017). In the same vein, Voodoo Manufacturing hosts 160 3D printers managed almost entirely by robots, allowing high levels of flexibility and customization, as well as non-stop, 24-7 production runs. Voodoo can take orders ranging from one to 10,000 units, serving companies such as Nickelodeon, Microsoft, and Mattel (Kolodny, 2017). These two start-ups, and many others, are taking important steps towards the goal of highly autonomous factories.

In addition to its automation and customization advantages, 3DP is a versatile tool that can be used in very different sectors for a broad range of applications. In biology, for example, bioprinting is being used to print cell suspensions and tissues (Mitchell, 2016); and in physics, two-photon lithography is employed to make nanotubes and micro tools (Saunders, 2017). The medical industry prints custom implants and prostheses, aerospace companies produce parts of satellites and engines, and the shoe industry makes custom sneakers with this technology. 3DP also works well at different scales; it is used in nanomanufacturing to print micro-lenses and micro-prisms and in construction to build bridges and houses. Moreover, 3DP can work with an increasing number of feedstock: organic materials, (semi) metals, composites, ceramics, and polymers. But despite the broad range of domains and applications for which 3DP can be used and the printing sizes and materials it supports, the technology today is nowhere near its full potential and has yet to overcome several printing quality and stability issues, as well as scalability problems (Martinsuo & Luomaranta, 2018).

2.3.3.2. 3D Scanners

A 3D scanner extracts a 3D digital model from a physical object by capturing information about its shape, dimensions and colors (Tóth & Živčák, 2014). The scanned data, made up of 'point clouds' in a spatial coordinate system, can then be processed by design software. Depending on their construction, scanners can be stationary or mobile, and depending on their procedure, they can be contact or non-contact (Mongeon, 2015; Tóth & Živčák, 2014).

2.3.3.3. Manufacturing Software and CNC Machines

CAD is the use of computer programs for design and documentation. CAD helps to visualize ideas digitally and renders manual drafting unnecessary (Autodesk, 2017). *Computer-Aided Engineering* (CAE) serves to monitor and analyze the performance of components and assemblies, and enables product simulation and optimization (e.g., stress and thermal analysis of assemblies). *Computer-Aided Manufacturing* (CAM) refers to the use of software to control machinery manufacturing and to assist planning, management and transportation in a factory (Leão, 2017). *CNC* machines work by gradually cutting or removing material from a block to create an object. CAD and CAM software provides the cutting instructions for the machine to operate rapidly and precisely (T. Rogers, 2016).

2.3.3.4. Laser cutters

These tools use a laser beam that moves in a two-dimensional plane to cut out flat sheets of plastic, wood, cardboard or metal. According to Gershenfeld, Gershenfeld, and Cutcher-Gershenfeld (2017), the laser cutters are the most popular tool in a Fab Lab; they can be fast and easy to use, inexpensive, and can cut complex shapes used to assemble 3D objects.

2.3.3.5. Digital Twins and Digital Threads

While the *digital twin* and *digital thread* concepts emerged in the United States Air Force (USAF), they have now spread to the broader world of Industry 4.0, cyber-physical systems and smart manufacturing (Leiva, 2016). A digital twin is a virtual representation of an object at every stage of its production and usage process (Chavali, 2017). This representation includes CAD information, product specifications, material properties, and simulation information. The digital twin complements the digital thread by keeping a virtual copy of the produced object evolution, increasing product reliability, and helping a firm migrate from products to services with more value added (Fraser, 2017). A satellite engine, for example, would have an identification number tied to its virtual model, with information about its thermic and deformation models, changes during manufacturing, material properties, inspection and maintenance, and deviations from the original design.

A digital thread "is the creation and use of a digital surrogate of a material system to allow dynamic, real-time assessment of the system's current and future capabilities to inform decisions" (USAF, 2013). The digital thread may be necessary to scale processes such as 3DP, which is increasingly connected and data driven. In the 3DP sector, the digital thread may facilitate scalability by exchanging information from disparate 3DP applications, printers, processes and data across firms.

According to Hennessey (2017), the digital thread may facilitate the integration of manufacturing processes. This integration has several challenges and rewards. Regarding the challenges, it requires large investments, cultural change, retraining, and the aligning of digital technologies (e.g., 3DP, IoT) with planning and management systems (e.g., Enterprise Resource Planning). Moreover, it may involve sharing sensitive information, establishing alliances, and unifying standards, which are necessary to develop interoperability across firms. Another challenge is ensuring cybersecurity; since digital processes and information exchanges are more critical, firms become more vulnerable to hackers, information leaks and viruses. According to Hennessey (2017), the potential rewards from a digital thread can be far-reaching. First, it enables the information flow to interconnect and facilitate processes horizontally across factories and vertically through the value chain. Fluid data sharing across the value chain not only helps reducing costs; it also facilitates the creation of more valuable and personalized designs and the creation of new services. Second, it improves decision-making by better integrating siloed functions (e.g., design, production), facilitating information exchange and providing real-time business insights. Third, the digital thread may lead to better product lifecycle tracking and quality. Closely gathering and analyzing data allows the early identification and prevention of production problems and facilitates documentation and certification processes. Hence, it is easier to assure better quality and reduce reprocessing and waste. Finally, the digital thread allows a deeper understanding of how a new product evolves from conception to usage. Having a detailed virtual model of a product at every stage, engineers can more easily predict potential performance, failures and the likely impact of various changes.

2.3.3.6. Generative Design

In addition to digital twins and digital threads, *generative design* is another tool that can speed the conception, design and production of innovative products. Generative design systems are defined as "systems aiming to support human designers and/or automate parts of the design process through computational means" (Singh & Gu, 2012 in Nordin, 2018, p. 16). With generative design, designers introduce goals, restrictions and input parameters such as weight, strength and dimensions to the software (e.g., Autodesk's Dreamcatcher and Fusion 360), which designs several 3D models based on such constraints. This creative interaction between designers and their software can save time and money while expanding the range of possibilities explored. The designer only needs to specify the parameters he or she wants in the final design and select the models generated by the software that best match the manufacturing restrictions, the aesthetic features, and the customers' requirements (Brown, 2017). Autodesk, Airbus, and APWorks, for example, partnered to use AI-based generative design, 3DP, and advanced materials to create a partition -a dividing wall between the seating area and the galley of a plane- that is stronger and 45% lighter than current designs (Grunewald, 2015). Generative design may thus reduce the use of material resources and the number of iterations required to manufacture a final product, while helping to explore a broader range of solutions to any design challenge, and freeing designers to focus on high-level tasks (McKnight, 2017).

2.3.4. Additional Features of Innovation-Driven Microfactories

2.3.4.1. Crowdsourcing

The 'wisdom of crowds' can be a fundamental element to the success of innovation-driven MFs. Crowdsourcing is "the act of outsourcing tasks originally performed inside an organization, or assigned externally in form of a business relationship, to an undefinably large, heterogeneous mass of potential actors" (Hammon & Hippner, 2012, p. 163). Web 2.0 implementation, greater computational power, better algorithms and hardware and data-storage cost reductions have facilitated the deployment of crowdsourcing initiatives. MFs often use crowdsourcing to access a large and diverse community of customers, experts and amateurs to provide new design ideas and to overcome some of the design, fabrication and security challenges that arise in making a new product. Such a community usually:

- Helps in reducing costs. Product designers and programmers participate in a project for little or no remuneration and community members can use word-of-mouth to help in marketing products, thus reducing design and marketing costs.
- Provides feedback to improve products based on customer expectations and expert advice. The community can generate ideas to make products better tailored to the needs of specific markets.
- Is a source of inspiration and creativity that foster innovation within MFs. It is often due to community input that MFs are constantly exploring new innovative solutions.
- Promotes an open innovation culture, making information available to everyone involved in any given project and even across projects.

2.3.4.2. Crowdfunding

Crowdfunding is defined as "an open call, essentially through the Internet, for the provision of financial resources either in form of donation or in exchange for some form of reward and/or voting rights in order to support initiatives for specific purposes" (Schwienbacher & Larralde, 2010, p. 4). There are three main crowdfunding approaches for innovation projects: entrepreneurs solicit individuals either to pre-order the product, to advance money in exchange for a share of future profits or equity, or to provide outright donations (Belleflamme, Lambert, & Schwienbacher, 2014). Pre-ordering a product is the most common source of funding for innovative projects. The success of platforms such as Kickstarter and Indiegogo has democratized the access to this kind of crowdfunding (Stephen, 2013). Crowdfunding has allowed several MF projects to:

- Obtain initial funding without need for venture capital, angel investors or loans. Hence, inventors and entrepreneurs will have more freedom to start and manage a new project or product launch, with little or no pressure to rapidly grow their revenue base. Thus, firm and market growth can be more gradual and manageable.
- Secure additional capital relatively fast. After a product is designed and the prototype is built, it is generally easier to receive funding. Some crowdfunding projects reach their funding goals within hours after launching a campaign.
- Help anticipate demand. If a project achieves its funding goals and it is funded by many people, it may have a substantial future demand. Crowdfunding platforms also facilitate communicating product progress to funders.
- Create buzz and a vibrant community around the project, even before the product has been launched. This allows inventors to know their customers' expectations early and to adjust the product based on those expectations.

2.3.5. Microfactories and the Maker Movement

Some communitarian grassroots initiatives, such as the Maker movement, share some of the distinctive traits of innovation-driven MFs. Dale Dougherty, MAKE magazine founder and Maker Faire creator, describes the Maker movement as a community of people with diverse backgrounds who come together in the physical world or in virtual spaces to share tools, knowledge and experiences in order to create useful new objects (Dougherty in Hagel, Brown, & Kulasooriya, 2014). According to C. Anderson (2012) the Maker community shares the spirit of the *do-it-yourself* (DIY) movement. According to Kneese, Rosenblat, and Boyd (2014), the DIY movement may have had its origins after the first Industrial Revolution in 19th century Britain, continued through the early and mid-20th century with the name of the Arts and Crafts movement, and gained popularity in the 1960s when several movements converged. After the ’60s, traditional DIY ideas of artisanal production, handicraft design, autonomy, affordability, creativity, reusability, and anti-consumerism started to couple with recent technologies.

These technologies, such as 3D printers, had the potential to leverage the capabilities of “Do-It-Yourselfers.” According to the website 3D Printing Industry , the earliest 3D printers were developed during 1980. In 1983, Charles Hull—cofounder and CTO of 3D Systems—invented the Stereolithography apparatus (SLA), which was patented as the first 3DP technology in 1986. In 1987, Carl Deckard, filed a patent for the Selective Laser Sintering (SLS) 3DP process, and in 1989 Scott Crump—cofounder of Stratasys—filed a patent for Fused Deposition Modeling (FDM). The invention of FDM was crucial because it is used by many of the entry-level 3D printers based on the open-source RepRap model, which abounds today. In the ’90s, many other 3DP technologies, applications, and materials were developed. However, despite increasing 3DP progress, these technologies were still expensive and used mostly by large industries as a prototyping tool. Do-It-Yourselfers did not have broad access to them.

It was not until the mid-2000s that 3DP became more available to the masses and started to connect with the Maker movement. In 2005, the RepRap project—short for Replicating Rapid-prototyper—became widely known. It is an open source and self-copying 3D printer that uses FDM to make 70% of its own parts and other products (Jones et al., 2009). RepRap is free and can be built with low-cost standard materials available worldwide. Hence, it became one of the technologies used by Makers and was complemented with other digital manufacturing technologies such as computer numerical control machines (CNC), 3D scanners, laser cutters, and CAD software. These are the common and basic technologies found in Makerspaces (C. Anderson, 2012), and in other similar community spaces offering public, shared access to high-end manufacturing equipment such as *Fab Labs* (Gershenfeld, 2012), *Hackerspaces* (Moilanen, 2012), and *TechShops* (K. Chen, 2013). Digital technologies allowed these community spaces to multiply, to work in collaborative projects with people around the world, and to share solutions to common technical problems.

There are some commonalities between innovation-driven MFs and the Maker movement, beyond the obvious fact that they both use digital fabrication technologies as core assets. Both leverage the wisdom of crowds to solve complex problems and design new products; both offer some shared spaces to foster creativity and innovation; and both attract young talents by constantly proposing challenges and exploring interesting new ideas.

Customization-driven MFs, on the other hand, have little to offer to, or to learn from, the Maker movement. Their core mission of providing customized products to their customers need not involve much innovation, except perhaps in the fast-fashion sector. They consequently tend to favor conventional business models, quite incompatible with the ethos and preferences of collaborative communities.

2.4. Implications of Microfactories

2.4.1. More Local Production and Shorter Supply Chains

The MF model is not about manufacturing vast volumes of products to serve national or international markets. Instead, it aims at building many small plants to serve local and regional customers (Géneau & Caulier, 2016). According to Wilson and Lumkes

(2015), local production offers several advantages. First, it facilitates direct post-sale contact with customers (e.g., support, repairs and warrantees). Hence, it enables a better understanding of customer needs and product usage, a more tailored customer service, faster repairs and shorter lead times. Second, it facilitates the creation of products more appropriate to prevailing local conditions. Third, the supply chain can be simpler, shorter and more efficient: since products are manufactured locally, much of the handling, shipping and storing of spare parts and subassemblies are no longer necessary.

2.4.2. Shorter Production Times

A readily available community of experts and customers, combined with digital manufacturing technologies, lead to MF agility. MF communities enable faster design, development and problem solving, which is fundamental to manufacturing innovative products. Digital manufacturing technologies eliminate retooling and allow faster product switching and flexible response, which in turn leads to shorter lead times, thus reducing time to market and allowing quicker responses to customers' orders (Wells & Orsato, 2005).

2.4.3. Customization and Product Variety

MFs can provide high customization levels due to digital manufacturing technologies. The synergy between these technologies "facilitates a more precise, efficient, flexible, and modular manufacturing in which the processes are interconnected" (Waldman-Brown, 2016a). Manufacturers can upload new designs, print them with less effort, and hence have faster product turnover. Digital manufacturing permits MFs to serve changing, competitive and dynamic markets in an agile way (Okazaki, Mishima, & Ashida, 2004). The factory floor can be easily and constantly reconfigured to facilitate production of additional new products. MFs render low- and medium-sized production runs viable.

MFs enjoy greater scope economies. MFs not only use flexible digital manufacturing technologies to manufacture disparate products, but also CAD software to design such products and to plan and streamline their production processes. The same set of software-driven tools can be used to design drones, cars or rocket engines. This experience of building a large variety of products for different markets reinforces MF mastery of the technologies and software they use, as well as their problem-solving capabilities, which allow them to manufacture an ever-larger variety of reliable products rapidly and inexpensively. Economies of scope are not just about cost reduction, they are also about product customization and the consequent market expansion (J. Rogers, 2017). To the extent that they can better target the needs of underserved niche markets, microfactories may increase the size and variety of markets, rather than compete with larger factories for existing markets.

2.4.4. Greater Sustainability?

MFs bring an approach to design and fabrication that may be more ecologically sustainable than traditional manufacturing. As stated before, MFs are heavy users of 3DP, which requires less feedstock and generates less waste in building a product; hence, under certain conditions, MFs can be more environmentally friendly. In addition, since MFs occupy less space and shrink supply chains by producing locally, they incur less carbon emissions and energy consumption (Williams, 2006). Moreover, better long-term customer service is possible, since the factory is closer to the market and it is easier to deliver replacement parts in a timely manner. The MF is also more suited to take care of repairs, maintenance and recycling, thus increasing the product's lifetime.

There are several aspects of 3DP that have a direct impact on the environment: energy, materials and fluids consumption, production time, morphology of the model, technology and material used, and nozzle efficiency (Bourhisa, Kerbrata, Dembinskib, Hascoeta, & Mognola, 2014; Tang, Mak, & Zhao, 2016). Another element that can have a considerable environmental impact is whether a product is modelled according to Design-for-Sustainable-Additive-Manufacturing principles; following these principles, the designer imposes some restrictions on the model so as to use fewer components and resources (Bourhisa et al., 2014; Tang et al., 2016). In general, very complex products that traditionally require multiple manufacturing steps are more environmentally friendly via 3DP, because several production steps are eliminated.

2.4.5. On-Demand Fabrication

Digital manufacturing technologies, crowdsourcing and crowdfunding have allowed MFs to transform the dynamics of economies of scale and scope in ways that may enable on-demand fabrication (Figure 7). The dream of on-demand fabrication is an old one. Gustavus Swift, in the late 1870s, built his meatpacking empire by using rail and telegraph technologies to link order intake from retail butchers, with procurement of cattle supplies, (dis)assembly, and final marketing in close to real time (Fields, 2002). Similarly, in 1996, Michael Dell started experimenting with the Internet to link "order intakes with procurement, production, and delivery of PCs, creating an innovative 'direct-pull' production and distribution network" (Fields, 2002, p. 5). Along the same lines, today's digital platforms are able to capture high volumes of data about customers, processes and products to create value by providing actionable information in real time that streamline and automate processes. 3DP harnesses the power of direct manufacturing by reducing the time a product takes to be manufactured and tested, while eliminating many obsolete tasks and processes in the value chain. Shapeways, for example, allows its customers to design and send 3DP orders online. Before a product is printed, the customer knows the cost and estimated delivery time.

3DP and digital platforms enable consumers to order online, directly linking them with producers, but they also allow firms to profitably serve small market segments, operate with little or zero inventory, and reduce overall response times from order intake to delivery, thus customizing and democratizing on-demand fabrication (Berman, 2012). Based on these arguments, we propose that *microfactories enhance local on-demand fabrication.*

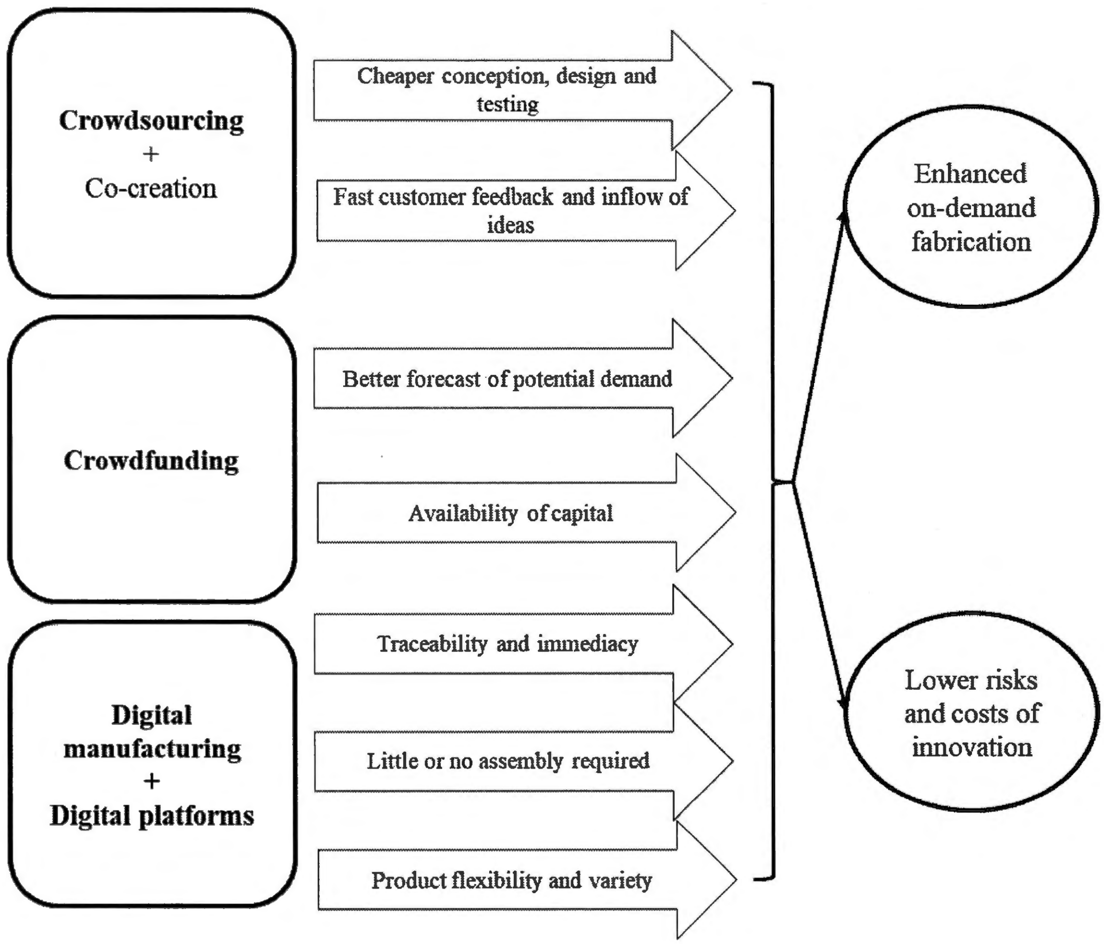
2.4.6. Lower Risks and Costs of Innovation

The combination of digital manufacturing technologies, crowdfunding and crowdsourcing also boosts the capacity of MFs to continuously experiment and develop new products (Figure 7). Flexible digital fabrication technologies let MFs manufacture diverse and customized new products in a short time, test different product configurations and evaluate a new product's performance in various contexts. The modular configuration facilitated by digital manufacturing technologies allows testing small batches of new products in several locations before scaling up production, thus lowering the likelihood and the cost of failed product launches (Waldman-Brown, 2016a). Crowdsourcing facilitates the inflow of new ideas and customer feedback, which will improve the match between what customers want and what is being offered to them. Crowdfunding facilitates raising capital to start or scale up product development and production. Constant innovation is an important driver for many MFs. A community of problem solvers and engineers capable of manufacturing directly from CAD files, speeds up product development, increases customization, reduces waste and redesign costs, and shortens the design-production time gap, unlocking MF innovation and speed-to-market capabilities. Crowdfunding and low fixed costs reduce the overall investment required to develop and launch innovative products. If an MF product is designed by a team of experts and potential customers, if it reaches its crowdfunding goal, and then goes on to sell well, these are strong clues that perhaps millions of units should be manufactured in a larger manufacturing plant to reach a much broader audience. Technological, funding and operational advantages thus give MFs the flexibility and adaptability to respond more effectively to market changes.

If demand turns out to be higher than a MF can optimally handle, it is less risky to migrate manufacturing to larger plants because the product is already designed, developed, produced in small batches, and tested by customers. This volume up-scaling may also be easier because the whole process is digitized, facilitating the codification of how the original product was designed, manufactured and tested. Although large incumbents are not attracted by niche markets, they may have to pay increasing attention to the world of MFs, should the latter become the preferred agents of product innovation.

MFs often have lower fixed and variable costs than conventional factories (J. Rogers, 2017). MFs frequently use open source designs, often provided by users without monetary compensation, hence reducing design costs. Moreover, since MFs are small, initial investments and operating costs are much lower than those of large factories. MFs, for example, may not require a large and dedicated service water and electricity infrastructure. Additionally, MFs operate on-demand, reducing the expenses of holding high inventory levels. Also, while traditional manufacturing needs large distribution networks – incurring high fixed and variable costs – a MF often sells its products on-site, without intermediaries, shipping or import/export costs; hence, distribution costs can also be much lower. In addition, 3DP generally allows for a vast reduction in the number of components, thus eliminating dozens or hundreds of tasks, and significantly reducing labor costs. Based on the arguments discussed above we suggest that *microfactories reduce the risks and costs of innovation.*

Figure 7. How Microfactories Stimulate Innovation and On-demand Fabrication



To summarize, crowdsourcing may allow for cheaper product development and speed up customer feedback and the inflow of ideas, crowdfunding may facilitate demand forecasting and capital funding, while digital manufacturing and digital platforms may ease traceability, reduce assembly work, and increase product flexibility and variety. Ideally, this can improve on-demand fabrication and lower the risks and costs of innovation.

2.5. Conclusions and Further Research

This article contributes to the discussion on the economic advantages and disadvantages of scale and scope, which have been insufficiently explored in the digital domain. More specifically, it explores the microfactory model, the elements that enable it and its implications. We have argued that MFs may reduce the risks and costs of innovation and that they may move various industries toward more local, adaptive and sustainable business ecosystems. Given its versatility and high degree of automation, the MF model may also fill the gap between artisanal and mass production processes, boost the rate of innovation, and enable local on-demand fabrication of customized products.

Currently, manufacturers generally need to make large investments when launching a new product, despite high uncertainty about customer acceptance, thus risking considerable losses. A MF offers a safer alternative by allowing a firm to develop and fabricate new products and test their acceptance in a local market before mass producing them. MFs also enable local on-demand fabrication of highly customized products.

Classic scalability has meant economic viability at large scale, due to the spreading out of fixed costs over an ever-growing output volume. The MF model changes the growth equation for startups in at least two ways. First, having little or no need for venture capital, startups will not be so hard pressed to maximize revenue growth. Second, not needing to ramp up rapidly and half-blindly into mass production, they can grow every successful project more gradually and organically, without compromising the firm's survival in the process.

Will MFs disrupt the industrial status quo? Probably only in those markets craving more personalized products, such as shoes, medical implants and office chairs. But beyond that, the impact of MFs will be immense in the crucial world of product innovation. All great innovations (e.g., semiconductors, lasers, GPS, LEDs, LCDs) started out by being useful in some small market niche. So, the option value of being able to colonize a large number of niche markets is much more important than the immediate value captured by the initial clienteles. Every new niche that is served by MFs adds value to a few clients. However, more importantly, some of those experimental bets will turn out to be so good that they will eventually impact the entire population, possibly improving the lives of millions. In this context, and although they are not attracted by niche markets, large incumbents may have to pay increasing attention to the world of MFs, should the latter become the preferred agents of product innovation.

Many questions regarding the likely future of MFs remain open. For example, in which industrial sectors might MFs have the greatest impact on the rate of innovation? Which MFs will be more plentiful in the foreseeable future, standalone MFs or MFs belonging to large companies? In what ways will innovation-driven MFs affect the interactions between firms and collaborative communities? How rapidly and to what extent might MFs affect reshoring and international trade? How might a switch toward more local fabrication affect the abundance and type of available jobs in industry? We hope to be able to address some of these questions in future research. In a subsequent paper about local on-demand fabrication, we intend to broaden the range of sectors analyzed and we will cover in greater detail the various types of MFs that are emerging.

3. CHAPTER III: LOCAL ON-DEMAND FABRICATION: MICROFACTORIES AND ONLINE MANUFACTURING PLATFORMS

Abstract: Recent technological advances, notably additive manufacturing and more flexible, versatile and affordable robotics, have enabled on-demand fabrication in ways that were not possible before. Some scholars and policy makers claim that these technologies and the business ecosystems they enable may strengthen local production and bring manufacturing facilities back to advanced countries. But other authors argue that local fabrication will remain relatively marginal and will not fundamentally change global trade and supply chains in the foreseeable future. The purpose of this article is to contribute to this ongoing discussion by exploring a particular type of on-demand fabrication unit, the microfactory (MF). We identify, classify and contrast several MFs and we propose a taxonomy emerging from the empirical data. We also identify and explore online platforms that complement certain kinds of MFs. To do so, we implement a multiple case study, triangulating data available on the web with interviews. We also use a novel type of experiential research: we perform some transactional activities (e.g., order the design and manufacture of a product) to validate the MFs' or the platform's claims and to better understand how they work. We select and assess 71 cases (61 MFs and 10 platforms) in 21 different countries, mainly in the manufacturing industries: electronics, machinery and equipment, motor vehicles, pharmaceutical, spacecraft, and clothing. The information was gathered and analyzed between August 2018 and April 2019. The results suggest that there are two main

dimensions that differentiate various types of on-demand fabrication units: their relative level of automation and their relative openness to external independent agents. Using these dimensions, we create a taxonomy of MFs. MFs with relatively low automation and high openness tend to be innovation-driven microfactories (IDMFs), aimed at reducing the risks and cost of innovation by enabling gradual scalability in new product launches. MFs with relatively high automation and low openness levels tend to be customization-driven microfactories (CDMFs) that seek instead to democratize product customization for local markets on an on-demand basis, generally focusing on a narrow set of products. And MFs with relatively low automation and low openness tend to be classic machine shops (MSs) offering local, small-scale manufacturing of a broad set of parts and products for a variety of industries. Regarding platforms, the results suggests that there are closed online manufacturing platforms (COMPs), which optimize the industrial equipment and installations of major manufacturers and their clients, and multisided online manufacturing platforms (MOMPs), which connect customers with independent fabricators. MOMPs, in turn, can be low-end or high-end, depending on the market segment that they cater to. This study reassesses the traditional notions of MFs and multisided platforms and offers, we hope, some insights which can help us to better understand the reality and potential of local on-demand fabrication. We conclude that while COMPs will greatly enhance the performance of large manufacturers, MOMPs will likely enable small firms -and not just small factories- to thrive in a more localized manufacturing landscape. Going forward, both large and small manufacturing firms can coexist; but the success of small fabricators (especially classic machine shops) will hinge on their ability to team up with leading-edge MOMPs. In a world where online platforms are becoming central to the reinvention of manufacturing, multisided online platforms and small fabricators will become strongly symbiotic: neither one can succeed without the other.

Keywords: On-demand fabrication, local manufacture, microfactories, online manufacturing platforms, digital manufacturing, additive manufacturing, case studies, experiential research.

3.1. Introduction

In the coming decades, new technologies are more likely than mercantilist policies to curb, and perhaps reverse, the trend toward global value chains. When it comes, the reshoring of manufacturing processes in advanced countries will be the convergent result of several vectors enabling local on-demand fabrication (Hagel, Brown, Kulasooriya, Gif, & Chen, 2015; Waldman-Brown, 2016a). Several companies are already developing more localized regimes of on-demand production: Adidas, for example, has partnered with Carbon to 3D print on-demand customized shoes in the U.S. (Dillet, 2018); Boeing is heavily investing in 3D printing (3DP) to manufacture parts internally, shortening its supply chain and accelerating production (Boeing, 2018); Nike is increasingly using online platforms and digitalization to have a more direct and fluid contact with customers, facilitating on-demand production and bringing products to market faster (Kapadia, 2018), and 3D Hubs is leveraging its platform to connect customers, needing a part, with local fabricators ready to serve them. In this paper, we explore different types of MFs and manufacturing platforms. We classify and contrast them highlighting their diversity, similarities and complementarities by means of a taxonomy and a conceptual framework[8].

MFs are fabrication units optimized for the small-to-medium-scale manufacture of a variety of products by using digital technologies (Montes & Olleros, 2019). Local

[8] A taxonomy is a classification method that generally emerges from the empirical data and involves comparisons between comparable cases. Typologies, on the other hand, are primarily conceptual constructs (Bailey, 1994). Despite such differences, many authors use these two terms interchangeably. In either case, a classificatory framework is the general process of grouping entities by similarity (Bailey, 1994).

Motors, for example, uses a network of small-scale facilities to 3D print vehicles on-demand to serve local markets.

Multisided platforms are physical or virtual hubs that facilitate the interactions between two or more distinct groups of customers who can create value for each other (Evans & Schmalensee, 2011). In this research, we focus on virtual platforms in the manufacturing domain. For example, Xometry and 3D Hubs are two-sided platforms that connect firms or people needing to make a part or a prototype with nearby fabricators with the technology and skills to do so.

This study is based on and contributes to the on-demand fabrication and online platform literatures. Most of the on-demand fabrication literature focuses on the optimal use of new technologies (e.g., 3DP and 3D scanning) and simulation techniques (e.g., optimization algorithms) to achieve on-demand manufacturing. And until recently, the online platform literature has rarely focused on the manufacturing domain, mostly emphasizing legal and regulatory elements, competition law and property, labor and employment implications, and business transformations. To our knowledge, none of the previous studies attempts to analyze, classify and compare on-demand manufacturing firms from an economic and business model perspective. Moreover, little research has been done on the platforms that are currently emerging and on their role in local fabrication ecosystems. This research tries to reduce this gap by addressing three questions: *What are the different types of MFs currently operating and how can we best classify and compare them? What are the different types of online manufacturing platforms currently operating and how can we best classify and compare them? To what degree and in what conditions do MFs and online platforms need each other to survive and thrive?*

We carried out a multiple case study to answer these questions. We started by using some techniques employed in systematic literature review to identify, classify and contrast 61 on-demand fabrication firms and 10 platforms from online sources (websites, magazines, YouTube videos and blogs). We complemented this information with semi-structured interviews, physical or virtual tours to some of the MFs' headquarters, and some instances of "experiential research". The latter consisted of carrying out several activities (e.g., asking a MF to design and manufacture a product) to validate a MF's or online platform's claims and to better understand how they work. The organizations selected are headquartered in 21 different countries, most notably Canada, Belgium, England, Finland, France, Germany, Kenya, Russia, the Netherlands, and the U.S. They operate mainly in the manufacturing industries (as per the OECD industrial classification): electronic, machinery and equipment, motor vehicles, pharmaceutical, spacecraft, and clothing. The information was gathered and analyzed between August 2018 and April 2019.

This study makes several theoretical, practical and methodological contributions. At the theoretical level, it reassesses the established wisdom about MFs and OMPs and offers a clearer conceptualization of these two organizational types, which may help us to better understand the reality and potential of local on-demand fabrication. At the practical level, a better understanding of the advantages and disadvantages of the various types of on-demand fabrication approaches should enable better strategy, evaluation and policy choices. At the methodological level, we explore a new type of experiential research in which we try to observe, describe and interpret firms and platforms by carrying out low-cost transactional activities (e.g., ordering the manufacture of a custom product, or solving a 3D model technical problem). Many details of a firm that are difficult to capture though interviews, secondary sources and netnography can be revealed this way.

The taxonomy of MFs that we propose in this paper involves two orthogonal dimensions that emerge from the empirical data: relative automation and relative openness. We track 'automation' as the degree to which manufacturing and sales processes do not require any human involvement. And 'openness' measures the extent to which MFs collaborate with, and seek funding from, an external and diverse community of independent agents, while perhaps facilitating the sharing of product designs within them. MFs can be found in three areas of an *automation-openness* diagram: weakly automated and open, highly automated and closed, and weakly automated and closed. Generally, we have found that the first of these are IDMFs, the second ones are CDMFs and the third ones are classic MSs. IDMFs aim to reduce the risks and cost of innovation by enabling gradual scalability in new product launches, CDMFs seek instead to democratize product customization on an on-demand basis and focus on one particular set of products and industry, and MSs aim to democratize small-scale manufacturing and have the capabilities to manufacture a broad range of parts and products for different industries. MFs can be *corporate* – belonging to large corporations and using their resources, goodwill and networks – or *independent* – standalone firms with their own resources and partners. Generally, MSs tend to be independent, IDMFs tend to be corporate and CDMFs can be either corporate or independent. As for online manufacturing platforms, they can be *closed* (COMPs) – enhancing the performance of major manufacturers and their clients by connecting and leveraging all their assets and data in real time – or *multisided* (MOMPs) – lean connectors that try to optimally match customers with independent fabricators and regulate/curate their transactions. Amongst the latter, we also found a difference between *low-end* MOMPs –which try to match amateur makers with amateur designers – and *high-end* MOMPs – which seek to match professional fabricators with industrial clients.

We conclude that while the rise of COMPs favors the predominance of large cross-sectoral firms with strong scope and scale economies ('pan-industrials', as D'Aveni (2018) calls them), the rise of MOMPs should favor the growth and success of independent fabricators. Thus, going forward, it should be possible for independent fabricators to thrive in a world of pan-industrial giants, but only if they team up with leading-edge MOMPs.

3.2. Literature Review

3.2.1. On-demand Fabrication and Digital Platforms

Westkämpfer (1997) defines on-demand manufacturing as a production method in which manufacture happens only in response to a customer's order, without any merchandise being stocked in anticipation of future sales. Following this approach, a firm tailors product features to customer preferences, machines can be reconfigured quickly and easily, and factories are located closer to local markets (Westkämpfer, 1997). Unlike traditional mass manufacturing, on-demand manufacturing does not require long and diffuse supply lines, expensive storage and long-distance transport. Also, and importantly, it obviates the risk of unsold inventory. The rising adoption of technologies such as CAD, 3D printing, 3D scanning and flexible robotic systems is making local on-demand manufacturing increasingly economic and compelling.

Mass customization, just-in-time production, distributed manufacturing, cloud manufacturing, agile manufacturing, minifactory and microfactory are some of the concepts associated with local on-demand fabrication. For Piller (2004, p. 315), *mass customization* refers to a "customer co-design process of products and services, which meet the needs of each individual customer with regard to certain product features. All operations are performed within a fixed solution space, characterized by stable but still flexible and responsive processes" allowing costs and prices to be lower than those of traditional customization. A *pull (or just-in-time) system* allows the production of goods to closely track demand fluctuations (Siha, 1994), thus facilitating lean manufacturing and reducing costs (Hopp & Spearman, 2004). *Distributed manufacturing* has been defined as "the ability to personalise product manufacturing at multiple scales and locations, be it at the point of consumption, sale, or within production sites that exploit local resources" (Srai et al., 2016, p. 6932). For Srai et al. (2016), in distributed manufacturing, customers' participation, digitalization and new manufacturing technologies play a key role in the product conception, fabrication and distribution. According to J. Zhou and Yao (2017), *cloud manufacturing* is a type of fabrication service in which complementary manufacturing resources are aggregated in the cloud and products can be delivered on demand. For Yusuf, Sarhadi, and Gunasekaran (1999), *agile manufacturing* refers to the integration of reconfigurable resources and best practices to efficiently reach higher levels of speed, flexibility, innovation and profitability. *Mini-factories* are flexible and compact manufacturing systems suited to fabricate personalized items close to customers (Barnia, Cortia, Pedrazzolia, Rovereb, & Lucisanoca, 2017) and *microfactories* refer to fabrication units optimized for the small-to-medium-scale manufacture of a variety of products by heavily using digital manufacturing technologies (Montes & Olleros, 2019).

Tiwana (2014, p. 5) defines a software *platform* as "an extensible software-based system that provides the core functionality shared by apps that interoperate with it, and the interfaces through which they interoperate." For Parker et al. (2016, p. 15), a platform is a "business model that uses technology to connect people, organizations, and resources in an interactive ecosystem in which amazing amounts of value can be created and exchanged." Multisided platforms are physical or virtual hubs that facilitate the interactions between two or more distinct groups of customers who can create value for each other (Evans & Schmalensee, 2011). As mentioned above, we focus on virtual platforms in the manufacturing domain (i.e., OMP).

3.2.2. Existing Work

3.2.2.1. On-demand Manufacturing: Three Branches of Literature

We used several elements of systematic literature review to explore the existing work on the field (Cronin, Ryan, & Coughlan, 2008; Paré, Trudel, Jaana, & Kitsiou, 2015). First, we selected the pertinent keywords: on-demand fabrication, on-demand manufactur*, on-demand production, mass customization, local value chain (see

ANNEX A: Keywords Scientific Literature). Second, we selected the inclusion and exclusion criteria (peer-reviewed documents in English, full text available). Third, we selected the bibliographic databases and scanned abstracts of the resulting documents after deduplication: Scopus (1760 documents), Proquest (118), Ebsco (347), Web of Science (908). Fourth, we read the most relevant papers (i.e., papers more aligned with our research question or with new/different theoretical insights) and searched for patterns in the literature. This review helped us to better understand and identify concepts related to on-demand fabrication.

There are three branches of literature related to on-demand fabrication, corresponding to hardware-driven, software-driven and strategy-driven approaches to on-demand manufacturing. The first branch deals with the methods, applications and technical viability of different hardware technologies for the efficient and customized on-demand fabrication of complex products. These technologies include, most notably, 3D scanning and 3D printing for on-demand fabrication of small batches of products in the medical (Hinze et al., 2015; Ware et al., 2018), pharmaceutical (Okwuosa et al., 2018; Sadia et al., 2016), chemical (Cao et al., 2017), electronic (Qin, Cai, Dong, & Lee, 2017) and spare-part industries (Jung, 2017). A second branch of literature – software-driven techniques or approaches to on-demand manufacturing – deals mostly with optimization algorithms (J. Zhou & Yao, 2017; L. Zhou, Zhang, Zhao, Laili, & Xu, 2018) and cloud-based applications (Ahn, Park, & Hur, 2016; Zheng, Feng, & Tan, 2017) and similar approaches to enhance on-demand manufacturing. The third branch of research deals with the design, production and supply chain strategies to efficiently manufacture on-demand. The most notable study in this branch, D. M. Anderson (2011), describes key factors that allow for successful and efficient implementation of mass customization (i.e., product families, standardization, flexible processes). Moilanen and Vadén (2013) analyze a broad set of 3DP uses and the demographics of the 3DP community. In the same vein, Rayna and Striukova (2016b) provide an overview of the main activities and key services of online 3DP platforms. The authors focus mainly on 3DP and explore a limited set of cases.

Overall, studies of on-demand manufacturing are scarce, limited in scope, and do not compare and classify different MFs within a larger context. The available studies focus mainly on 3DP, a key element of the on-demand fabrication ecosystem, but not an isolated technology. Moreover, none of them highlight the increasingly important interplay between online manufacturing platforms, automation, scaling and openness for local fabrication. We intend to bridge this gap and contribute to a better understanding and classification of a range of local on-demand fabrication units enabled by emerging technologies.

3.2.2.2. Platforms: Existing Literature

In this subsection, we followed a method similar to the one described in the previous subsection. The research on online platforms comprises studies of the sharing economy, the digital economy, digital marketplaces, and multisided markets. It is generally concentrated in four main domains: legal and regulatory elements, competition law and property, labor and employment implications, and business transformations.

The first domain – legal and regulatory elements – addresses questions on how to keep platforms accountable (Duguay, 2018; Goldkind & McNutt, 2019) and secure (Fraile, Tagawa, Poler, & Ortiz, 2018), how to regulate (Finck, 2018; Thelen, 2018) and enforce law on global, boundaryless platforms (Leshinsky & Schatz, 2018; Wattecamps, Kleczewski, & Marique, 2017), how to protect the privacy of platform users and the data generated (Evans, 2019; Salmony, 2018), and how to deal with surveillance issues (Schneider, 2018; Woods, 2018). The second domain – competition law and property – focuses on antitrust law and policy (M. L. Katz, 2019; M.L. Katz & Sallet, 2018), anticompetitive conduct (Bostoen, 2018), platform merges/acquisitions (Evans & Noel, 2008; M. Zhou, Leenders, & MeiCong, 2018) and intellectual property (Jakobsson & Stiernstedt, 2012; Niculescu, Wu, & Xu, 2018). The third domain – labor and employment implications – emphasizes the impact of platforms on work conditions (Meilhan, 2019; Veen, Barratt, & Goods, 2019), job creation (De Groen, Kilhoffer, Lenaerts, & Salez, 2017; Drugău-Constantin, 2018), employment relationships (Fricke, 2019; Gramano, 2019), and social security (Schor, 2017; Schor & Attwood-Charles, 2017). The fourth domain – business transformations – deals with sectoral transformations enabled by platforms (Nieborg & Poell, 2018; Ruggieri, Savastano, Scalingi, Bala, & D'Ascenzo, 2018), and new business models (Akbar & Tracogna, 2018; Münzel, Boon, Frenken, & Vaskelainen, 2018), the impact of platforms on entrepreneurship (Chandnaa & Salimath, 2018), and future trends on online platforms (Fehrer et al., 2018). Few of the above are concerned with the specific problems and opportunities that recent online platforms represent for the manufacturing sector.

3.2.2.3. Regime Changes

Overall, we have identified five types of manufacturing regimes that may arise in various sectors and countries in the coming years. First, simple *reshoring* as a general strategy to relocate manufacturing plants closer to firms' headquarters and to enhance the local manufacturing ecosystem (Wan, Orzes, Sartor, Di Mauro, & Nassimbeni, 2018). Second, *reshoring combined with on-demand customized production.* This is a regime that Richard D'Aveni (2018) sees rising across the developed world in the coming years. According to this author, giant networks of multisectoral 3DP-based and software-driven companies ('pan-industrials', as he calls them) will likely dominate the manufacturing landscape. While 3DP will allow these companies to have increasing flexibility, customization capabilities and modularity, software platforms will allow them to gather vast amounts of data, coordinate complex tasks and increase efficiency. Third, *reshoring combined with on-demand manufacturing and MFs*. This regime is similar to the previous one, but here MFs play an important role in decentralizing manufacturing, producing nearer to the customer, and shrinking and localizing the supply chain (Wells & Nieuwenhuis, 2011). The fourth regime is based on *reshoring combined with on-demand fabrication, MFs and a set of smaller technology-driven firms* capable of reducing the current predominant role of giant manufacturing companies (C. Anderson, 2012). In a fifth regime, some people foresee a surge of *reshoring and on-demand fabrication* via communitarian *FabLabs* and other *makerspaces.* According to the Fab City movement, this regime will become so effective that cities should be able to approach economic self-sufficiency: they would produce everything they consume in an ecological, inclusive, do-it-yourself way (Fab City, 2019). Waldman-Brown (2016b) has criticized this particular vision by arguing that while the Maker movement may facilitate pilot projects, decrease prototyping costs, and foster entrepreneurial ecosystems, it is unlikely to replace traditional market-based alternatives, be they large or small.

Overall, this diversity of possible manufacturing regimes suggests that the surge of manufacturing reshoring in advanced countries need not be communal and distributed in terms of ownership and governance. While perhaps smaller and more local, tomorrow's factories may well be more vertically and horizontally integrated than today's because of 3DP's minimal setup and assembly costs and the consequent scope economies (D'Aveni, 2018). In addition, firms may also want to be more vertically integrated (across the various factories belonging to the same firm) because it will be the best way to protect their intellectual property in a world of affordable 3D printers and scanners. Moreover, as D'Aveni has emphasized, tomorrow's manufacturing giants will likely be a lot more multi-sectoral than they are today.

3.2.3. Initial Research Assumptions

On the basis of previous readings and before starting our methodical data gathering and analysis, we assumed that there were several kinds of economic agents in the local on-demand fabrication ecosystem. First, IDMFs, which try to reduce the risks and cost of innovation by enabling gradual scalability in new product launches. Second, CDMFs, which seek instead to democratize product customization on an on-demand basis for local markets. Third, OMPs which seek to complement those two types of MFs by intermediating between designers, manufacturers and final customers. We also assumed that a set of distinct features would facilitate the classification and analysis of these agents (see Table 9 for some examples).

Table 9. Local On-demand Fabrication: Initial Assumptions

		Degree of automation	Freely shared designs	Open shops	Crowdsourcing	Crowdfunding
IDMF	Local Motors	Medium	Sometimes	Rarely	Yes	Yes
	FirstBuild	Medium	Sometimes	Yes	Yes	Yes
CDMF	Adidas SpeedFactory Lab	High	No	No	No	No
	AM4U	High	No	No	No	No
OMP	Opendesk	Medium	Often	No	Yes	Yes
	3D Hubs	High	Sometimes	No	Yes	No

IDMF: Innovation-driven microfactory CDMF: Customization-driven microfactory
OMP: Online manufacturing platform

3.3. Methodology

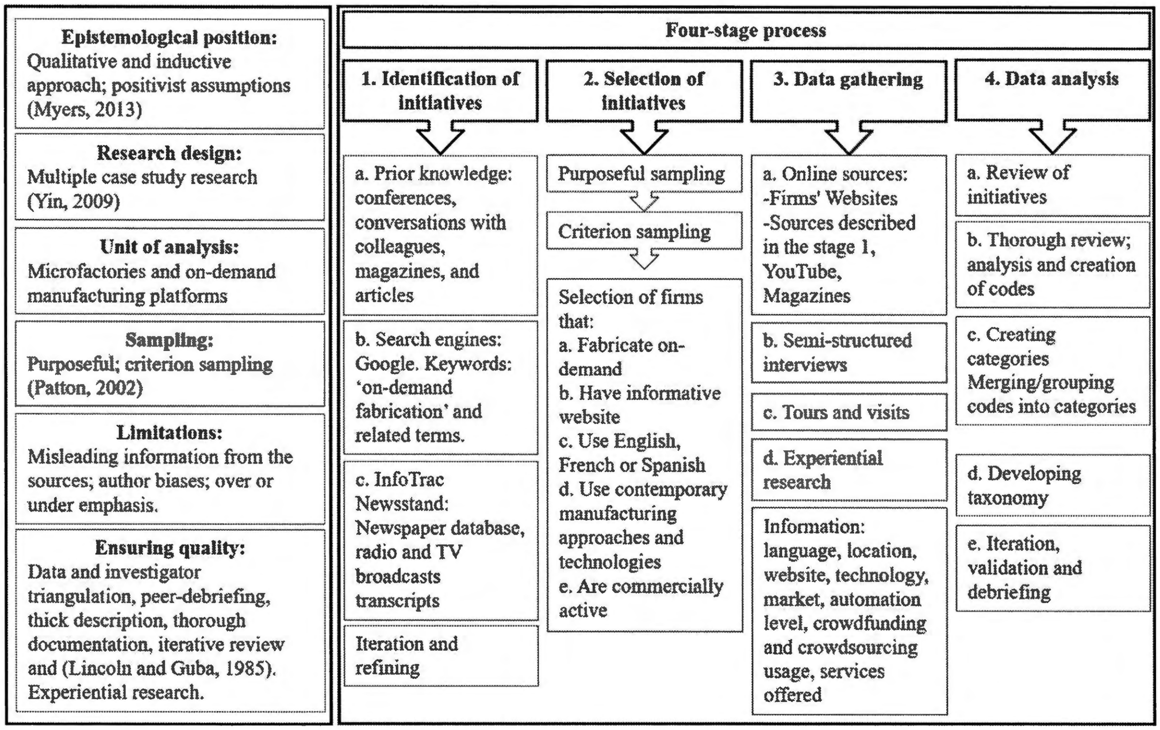
3.3.1. A Qualitative Inductive Approach

To better understand, contrast and classify the different MFs and OMPs, we implemented a qualitative inductive approach that tries to extract meaning from the data (Hesse-Biber, 2016) and understand the context (e.g., MF) in which actions take place (Myers, 2013). Three reasons lead us to approach our research questions via a *multiple-case study research* (Yin, 2009). First, case studies are well suited to analyze a contemporary phenomenon, such as on-demand fabrication, within its real-life context (Yin, 2009). Second, case studies facilitate in-depth and holistic descriptions (Yin, 2009). Third, this method allows us to better assess the meaningful characteristics of the subjects studied (Yin, 2009).

3.3.2. Unit of Analysis, Sample, Data Sources and Data Analysis

Our main *units of analysis* are the MFs and the OMPs. We implemented a four-stage process (Figure 8) to identify and select the most suitable MFs and OMPs, gather information about them and analyze them. For an effective data triangulation (Patton, 2002; Yin, 2009), we gathered data from websites, interviews, virtual/physical tours and experiential research. This process was carried out between August 2018 and May 2019.

Figure 8. Methods: A Four-stage Process



3.3.2.1. Identification of Pertinent Firms

We used several sources to reliably identify on-demand fabrication firms (Table 10). First, we drew on our prior knowledge to spot the best-known on-demand manufacturing efforts introduced to us via conferences, comments from colleagues, manufacturing or technology magazines and journal articles. Second, we used the Google search engine to identify additional firms. Initially, we used the keywords "on-demand manufacturing", "on-demand fabrication", "mass customization", and related terms; later, we refined our keywords to get more accurate results (see ANNEX B: Keywords for Firm's Identification). We iterated this process until we reached saturation. Third, we looked for additional firms in InfoTrac Newsstand, a source of full-text databases that covers leading newspapers, radio and TV broadcasts and transcripts in several languages and across the world.

Table 10. Number of Firms Identified and Selected

Source	Number of MFs and OMPs identified	Number of firms selected
Previous knowledge	23	71
Previous scientific literature	16	
Google search engine	261 firms identified	
InfoTrac Newsstand	32 firms identified	
Firms identified from references in the websites of other firms	10	
Total	342	71

3.3.2.2. Selection of Firms

We used *purposeful sampling* aimed at selecting the most "information-rich cases" (Patton, 2002, p. 243). Specifically, we chose the firms that best met several predetermined criteria:

- Fabricate products on-demand or intermediate the search, matching and use of such services.
- Have a readily available website.
- Use English, French or Spanish as a working language or provide information on their websites in any of these languages.
- Rely heavily on new manufacturing approaches (e.g., cloud manufacturing) and digital manufacturing technologies (e.g., virtual prototyping, 3D printing and 3D scanning).
- Are commercially active.

The last criterion on this list led us to exclude all communitarian projects, such as Fab Labs and other types of makerspaces.

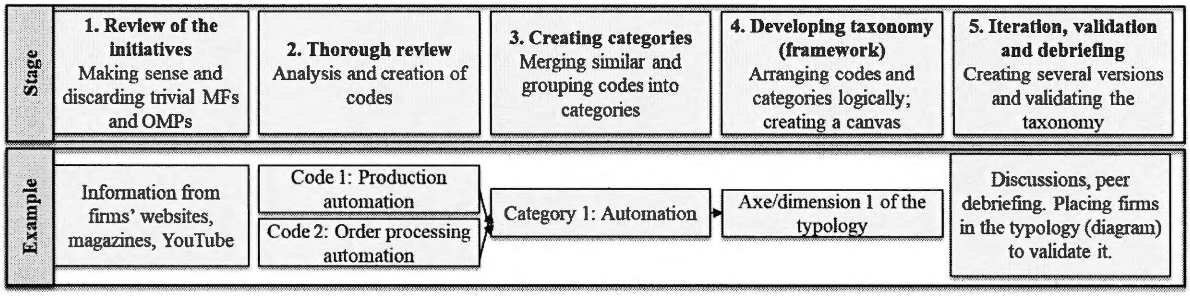
3.3.2.3. Data Gathering

After gathering information from the selected firms' websites, we triangulated the missing or confounding information with independent websites, manufacturing magazines and forums such as bloomberg.com, 3dprintingindustry.com and glassdoor.com (see ANNEX D: Independent Magazines and Websites). Interviews on YouTube and comments on those interviews helped us to better understand and assess the opinions of MFs' and OMPs' leaders. The names of the interviewees have been changed in this document, so as to protect their anonymity. Whenever possible, we watched virtual tours or visited MFs' headquarters; some virtual tours were available on YouTube or on the MFs' websites. The offline visits were either in groups (organized by the MF) or individually, upon our request. Initially, for each MF and OMP we tried to gather information about their location, technologies used, market served (sector and geography), degree of automation, crowdfunding and crowdsourcing usage, services offered, and any other relevant information to complete a table with separate cells containing this information. The websites' information was collected in Microsoft Excel, which helped us to classify and filter the data. We used semi-structured interviews to gather information not available online and to better understand the firms and their context (Hennink, 2011). The interview guideline (see ANNEX C: Interview Guide) followed the suggestions proposed by Hennink (2011): adapt the questions to each firm, if necessary; refine the questions to get information more efficiently and accurately; use probes; ask questions aligned with the research objectives; and try to use terminology familiar to the interviewee. Most of the interviews were recorded, and relevant sections of the audio files were transcribed.

3.3.2.4. Data Analysis

The data analysis involved five steps (Figure 9). First, we reviewed the firms selected to make sense of them, checked the information available, and discarded trivial information or irrelevant firms. We reviewed the information gathered, navigated through the firms' websites, and reviewed independent websites to validate or clarify the information.

Figure 9. Data Analysis



Second, we reviewed the firms thoroughly and created virtual post-it codes in Microsoft Excel containing keywords or short sentences about recurrent topics that emerged during the reviews. For example, when some MFs and OMPs mentioned the fact that they serve a small market, we created the code "niche market". Likewise, when several MFs mentioned usage of 3DP and other robots to manufacture and handle their products, we created the code "production automation". The firms' websites gave us information to create additional codes. For example, we created codes such as "order processing automation" and "process simplification" when we noticed that MFs and OMPs had their own automatic quoting or matching systems. Missing information also gave us useful hints. While some firms described their technologies, partners and projects in some detail, others were silent on such matters, thus leading us to question their level of sophistication and information sharing.

Third, we merged similar codes and grouped them into categories. We renamed the codes as needed, so they could match the information we were analyzing. For example, the codes "production automation" and "order processing automation" were grouped in the overall category "automation".

Fourth, we developed a graphic framework that contains our taxonomy. We arranged the main categories in a logical way, forming a canvas in which the MFs could be placed and classified. The main categories served as axes (dimensions) of the framework and the MF types emerged as combinations of specific levels along the various axes. We carried out a similar process for the online platforms.

Fifth, we iterated steps one to four until we found the taxonomy that best matched the MFs and OMPs information, their codes and their categories. The synthetic understanding of the information gathered and the firms' contexts, along with the investigator triangulation and peer debriefing were essential at this last stage.

3.3.3. Experiential research

For our purposes, we define experiential research (Table 11) as a naturalistic inquiry in the digital domain that consists of simulating or performing transactional activities to validate certain entities' claims, in our case MFs and OMPs. In some cases, for example, we ordered the design and manufacture of a product/piece from the firm, which allowed us to better gauge their response times, capabilities and interactions with customers.

Table 11. Experiential Research

What is it?	Advantages and disadvantages	Process		
		1. Selecting and planning	**2. Executing**	**3. Following**
a. Naturalistic inquiry in the digital domain b. Qualitative paradigm	**Advantages** a. Helps to gather information otherwise hidden or hard to get	a. Establish the criteria to identify the object	**a. Initiate transaction** Conduct the experience (e.g., open	a. Provide feedback (e.g., complete firms

What is it?	Advantages and disadvantages	Process		
		1. Selecting and planning	2. Executing	3. Following
c. Most suitable when the objects of study (e.g., firms) are known d. Multipurpose: helps to gather information, validate it and provide descriptions	b. Helps to better understand how a research object operates and interacts with its context **Disadvantages** a. Works better when complemented with other methods b. It can be expensive and hard to implement	b. Search and select the object c. Define the goals d. Define the process to explore e. Gather and make sense of the object information that is readily available f. Establish timing and a budget g. Establish actions to reduce annoyance on the object	account, select parameters, upload models, order a product) **b. Establish contact** - Interact with the object (e.g., interact with personnel of a firm via chat, phone, e-mail) - Inquiry process (e.g., ask questions that a customer would normally ask) **c. Finish transaction** - Finish the experience (e.g.,	satisfaction survey) b. Answer e-mails and notifications from the firm

<table>
<tr><th rowspan="2">What is it?</th><th rowspan="2">Advantages and disadvantages</th><th colspan="3">Process</th></tr>
<tr><th>1. Selecting and planning</th><th>2. Executing</th><th>3. Following</th></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td></td><td>introduce address, make payment)</td><td></td></tr>
<tr><td colspan="3">4. Reporting and comparing</td></tr>
<tr><td></td><td></td><td colspan="3">This process is parallel to processes 1, 2 and 3. It consists on documenting the process, comparing what happens during the experience with the object's claims (from interviews, netnography and/or secondary data), and comparing objects among them</td></tr>
</table>

A search of "Experiential research" on the Internet and bibliographic databases shows that similar terms have been used in the past, but they did not refer to the methodology implemented in this chapter. An inquiry on the Internet shows that the term experiential research refers to:

- *General Experiential Learning:* Learning from experience or learning by doing (Brock University, 2019)
- *Experiential Marketing:* Giving products to potential customers so they can try or have an "experience" with them before buying them (Olenski, 2018)

A search on scientific databases shows:

- *Experiential Research:* A new research paradigm that breaks down the traditional distinction between the role of the researcher and the role of the subject. While in the traditional paradigm only the researcher thinks and generates conclusions from the research, in experiential research the subject takes an active role in the research process. Hence, those involved in the research are co-researchers and co-subjects (Heron, 1982).

- *Experiential Education:* A philosophy that informs many methodologies in which educators purposefully engage with learners in direct experience and focused reflection in order to increase knowledge (Bocarro & Richards, 1998; Kolb, 1984).
- *Experiential Learning:* Learning from experience or learning by doing. Experiential education first immerses learners in an experience and then encourages reflection about the experience to develop new skills, new attitudes, or new ways of thinking. (Lewis & Williams, 1994, p. 5)
- *Experiential Research:* "Research approaches that involve a tangible way of doing, such as arts-informed inquiry, are a means of making tacit ideas explicit and make new insights possible for both the researcher and the research audience." (Butler-Kisber & Poldma, 2010, p. 1)
- *Experiential Research (Psychology):* Taking the role/identity of someone else, in a physical context, to have an experience of how the daily life of others is. (Reynolds & Farberow, 1973)
- *Experiential Research (Team Approach):* Involvement of people with different roles (e.g., academics, consultants and entrepreneurs) in the research process, even when some of these people are part of the phenomenon being studied (e.g., entrepreneurs). (Grant, Gilmore, Carson, Laney, & Pickett, 2001)

3.3.4. Research Limitations and Quality Conditions

This work has three potential limitations. First, despite being open to scrutiny and criticism from customers, the information provided by the websites or by the interviewees could be biased or misleading. To reduce this problem, we triangulated the information from the interviews and MFs' and OMPs' websites with information from independent sources (see ANNEX D: Independent Magazines and Websites). We also asked some interview questions in different ways to check for inconsistencies, requested factual information and real-life examples, and inquired about recent events to spot recall biases. Second, we may have created a faulty taxonomy or may have classified some MFs and OMPs incorrectly. To minimize this problem, we used *investigator triangulation* (Patton, 2002), that is, each author of this study separately classified each firm. We then worked together to resolve our initial disagreements. Third, we may have overemphasized or underemphasized certain firms' features. To reduce this problem, we implemented *peer debriefing*. Through this technique, an external researcher, with knowledge of the research field and the methodology, critically reviewed the methods application and provided feedback on the results (Spillett, 2003), contributing to the credibility and reliability of our constructs. It would have been useful to interview some of the customers of the firms analyzed with the goal of adding more rigor to this research and contrast different opinions. However, having access to customers data is not easy. Firms tend to be very protective of their customers' information, for understandable and legitimate reasons.

Besides the strategies mentioned above, we used additional methods proposed by Lincoln and Guba (1985) to strengthen the credibility, transferability, dependability and confirmability of our results; we also adapted some of the criteria proposed by Aguinis, Ramani, and Alabduljader (2017) to increase transparency. To increase the credibility (i.e., the "truth value" or accuracy) of our results we documented our biases, verified our results/information with the interviewees and made a prolonged and persistent review of the data. Moreover, we iterated the data analysis and checked whether there were any MFs and OMPs that did not fit in the resulting taxonomy. To strengthen transferability (i.e., the degree in which the results can be applicable in several contexts) we followed the recommendations of Lincoln and Guba (1985), made a thorough description of the firms and the data analysis and kept records of the information gathered. Hence, readers will have enough contextual and procedural information to use our taxonomy to classify new firms at different times and places.

Experiential research was also important to increase the quality conditions, as it allowed us to validate the claims made by the MFs and the OMPs; for example, by ordering products, we were able to assess the extent of process-ordering automation, problems during manufacturing (and solutions), product traceability, delivery times and costs, and product customization possibilities. To increase transparency, we stated our initial research assumptions, disclosed search keywords and online information sources, and described inclusion and exclusion criteria.

3.4. Empirical Findings About Microfactories

The information we gathered (Table 12) shows that on-demand firms vary along two main dimensions: *automation* and *openness*. These dimensions encompass almost all the codes that emerged from the data and are present in the cases selected. Moreover, they allow us to classify and compare all the firms and fabrication units we have found. In our analysis, 'automation' refers to the degree of autonomy embedded into machines and software; this dimension ranges from low (poorly automated) to high (highly automated). 'Openness' indicates the degree in which MFs seek funding via online open calls (crowdfunding), take external ideas from a diverse community (crowdsourcing), and freely share their own designs, or those of their partners; this dimension ranges from closed to open. As in Figure 10, the horizontal axe corresponds to the openness levels and the vertical axe corresponds to the automation levels.

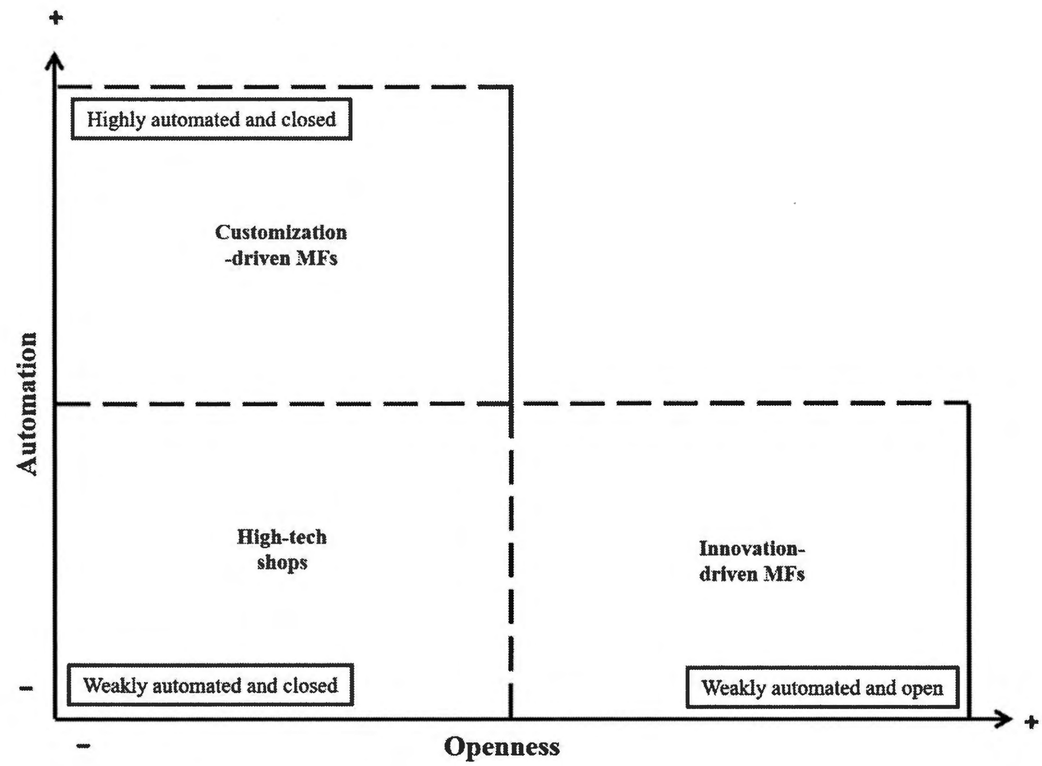
Table 12. Information Sources

Source	Type and quantity	Description
Interviews	Skype: 5 Zoom: 2 Phone: 1 Mail: 2	The interview length varied from 28 to 60 minutes; 37 minutes on average.

		The interviewees were mostly CEOs, founders, or directors of supply chain
Tours	Virtual: 17 Physical: 1	The virtual tours length was from 3 to 10 minutes; average duration 6 minutes. The physical tour length was 60 minutes.
Websites and electronic magazines	Independent websites and magazines: 49 Firm's websites: 83	
Experiential research	Transactions: 13	Budget: 150 CAD; the average duration of each experience was 3 hours spread over one week.
Countries	Australia, Belgium, Canada, China, England, Finland, France, Germany, India, Israel, Japan, Kenya, New Zealand, Nigeria, Russia, South Africa, Spain, Sweden, Switzerland, The Netherlands, USA.	

As the various MFs' business models evolve over time, their position in the figure may change. Moreover, the classification is polythetic, meaning that "initiatives pertaining to the same area are not identical on all variables, but rather a group of cases by overall greatest similarity; that is, they are more similar to the cases in their class than to the cases in other classes" (Bailey, 1994, p. 7).

Figure 10. Automation and Openness in Microfactories



3.4.1. Automation

We identified two different automation tiers in the cases explored: *automation in production* and automation *in order processing*. We measured production automation inversely by the degree of human involvement during a product's design, fabrication and testing. And we measured automation in order processing by the degree of reliance on digital twins, digital threads and automatic systems for order processing.

Despite such differences, we found that automation levels tend to be correlated across tiers. Thus, MFs characterized by *low overall automation* show low degrees of automation in both production and order processing. In these MFs, production often is automated via 3DP, which can eliminate many assembly tasks by printing entire products or components in one go. However, prototyping, product iterations, post-processing and product handling generally require human labor. Moreover, even though these MFs use digital platforms to connect with customers and collaborators, their orders are so small and varied and human-machine interactions are so frequent that order intake, processing and delivery are difficult to automate. The Autodesk Technology Center in San Francisco, for example, allows its customers and partners to develop exploratory projects that require several iterations, post-processing and refining. When we visited the center on a guided tour, we could grasp the complexity of the creations and the need for various people to tightly collaborate in-situ and in real time. In contrast with other MFs studied, those with low automation levels use diverse technologies simultaneously or in sequence, manufacture their products using different materials (e.g., plastic and metal), and fabricate a broad range of different products (e.g., buses, cars and drones). FirstBuild, a Haier initiative that crowdsources and manufactures small batches of innovative products, relies on a variety of technologies such as plastic mills, 3D printers, laser cutters, metal cutters and CNCs and is able to work with plastic, metal and wood, among other materials. They manufacture products as diverse as ice makers, water filters and drying racks.

Conversely, *MFs with high automation* in production tend to also exhibit high levels of order processing. Voodoo manufacturing, for example, uses mainly 3DP to make their products and has started to use robotic arms to assign and replace the plates on which the products are printed, a task that was previously done by humans. Their explicit goal is to automate the entire production process 24 hours, 7 days a week (Schwartz & Friefeld, 2017). On the order processing side, Voodoo allows its customers to upload their designs and adjust printing parameters (layers, material, infill) which are automatically sent for printing and shipped, the whole process is done directly on the platform ("Direct Print Now" service) with zero interaction between the customer and Voodoo's personnel. As an experiment, we used Voodoo's website to

3D print a dice model that we found on Thingiverse.com. In less than five minutes and with no human assistance from Voodoo, we uploaded the model, selected the printing parameters, got an instant quote, introduced our shipping address and credit card information for payment. The dice was printed in 11 hours and shipped from Voodoos' New York MF 24 hours after placing the order. We received text messages and e-mails informing us of each step in the process. We were offered the option to print and ship the dice faster for a higher price – an additional 6 USD or 49 USD respectively.

High-automation MFs tend to leverage a single manufacturing technology (e.g., only 3DP), use only one type of material (e.g., only polymers), and manufacture a narrow set of products (e.g., only insoles or only hearing aids) which can be highly customized. Invisalign and 3D Smile, in the fabrication of clear aligners for orthodontics, belong to this group. These companies take advantage of 3DP to manufacture their aligners using polymers. Since every person's orthodontic needs are different, Invisalign and 3D Smile customize with great precision and speed every dental aligner they make.

3.4.2. Openness

Our analysis showed that openness levels vary among microfactories. Some MFs show signs of *high openness*: they leverage crowdsourcing and crowdfunding and they share their designs freely. These MFs usually have their own crowdsourcing platforms that both connect the MFs with their online community of designers and problem solvers and showcase the challenges or projects in which they are working, so that the online community can participate in them. Some of these MFs also use crowdfunding platforms to secure project-specific funding relatively fast from numerous people via the Internet. Moreover, some of these MFs tend to favor free flow of ideas, designs and prototypes, as well as news about the advances made by their on-going projects. Such open firms often set up physical as well as virtual spaces to favor the exchange of ideas and collaboration. FirstBuild, for example, shares physical spaces for its community to ideate products as wells as the tools to manufacture them. Hundreds of people participate in the conception and improvement of some of Haier's products, which are eventually manufactured and tested, and finally launched to market. These products are protected with Creative Common Licenses, which facilitate the flow of designs in the community but also guarantee authorship attribution to the initial concept leader.

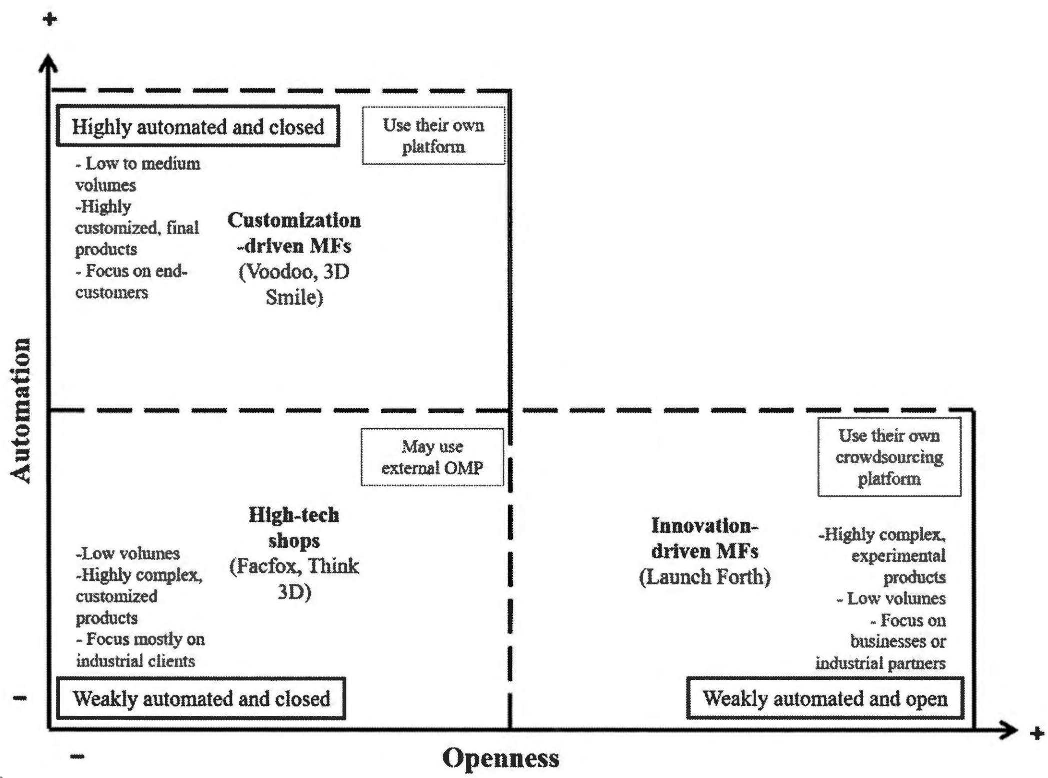
Other MFs show signs of *low openness*: they use neither crowdsourcing nor crowdfunding, and they restrict access to their proprietary designs. Such MFs often work for customers in the defense, aerospace and medical industries, and do not want to risk their products being copied or hacked. Consequently, while they work in tight collaboration with their customers, they are not interested in fostering a free flow of ideas within an open community. 3D Smile, for example, works closely with orthodontists to design and manufacture custom-made aligners. Moreover, since these MFs tend to be well established or funded by venture capital, they rarely use open calls on the Internet to raise funds. This kind of MF would never think of crowdsourcing its designs, or setting up crowdfunding campaigns to access financial resources. In the same vein, Sonova, which makes customized hearing aids, uses its own resources and engineers. Sonova's Aurora Operations and Distribution Center manufactures the external shell that protects the hearing aids' tiny and complex electronic components. Each of the 100 3D printers that the firm has installed in their manufacturing facilities in Canada, the U.S. and Vietnam can make 12 products per hour. Sonova relies on its own team of experts when problems arise.

3.4.3. The Automation-Openness Spectrum

As mentioned above, most of the MFs we analyzed can be classified in a diagram charting various levels of automation (along the vertical axis) and openness (along the horizontal axis). The MFs surveyed presented a set of features that allowed us to classify them in distinct areas shown in Figure 11: weakly automated and open

(IDMFs), highly automated and closed (CDMFs), and weakly automated and closed (MSs).

Figure 11. Automation and Openness



3.4.3.1. Weakly Automated, Open Microfactories

These MFs tend to exhibit high levels of openness: they use crowdsourcing for product ideation, prototyping and testing, they leverage crowdfunding campaigns to secure capital relatively fast, and they share designs and models for the community to comment on and improve.

Compared to other MFs in the overall sample, the automation levels of these MFs tend to be low, in both production and order processing. Even though they use 3DP, 3D scanning, generative design and other digital manufacturing technologies, human involvement is still considerable. Product ideation, brainstorming and testing are frequent, labor-intensive and time-consuming in these MFs. Professional and amateurs work together to solve technical problems and innovate.

Innovation-driven microfactories belong in this group. IDMFs try to reduce the costs and risks of innovation by enabling the gradual scalability of new product launches (Montes & Olleros, 2019). Local Motors in the motor vehicle manufacturing sector, Local Motors's Launch Forth in transport, robotics and defense, Haier's FirstBuild and GE's Fuse in home appliances, and Autodesk's Technology Center in design and manufacturing are prominent examples of this trend. In general, IDMFs work on highly complex and experimental products and tend to manufacture in low volumes. Since they are highly innovative, most of their efforts concentrate on brainstorming, product ideation, development and prototyping for industrial partners.

The Autodesk Technology Center, a microfactory located in San Francisco's Pier 9, is open to entrepreneurial communities beyond Autodesk's industrial partners. When we visited the center on one of their public tours, we noticed a large array of high-end manufacturing technologies and engineers and researchers working in collaboration. The center works with firms, university labs and entrepreneurs wanting to design and test new ideas and products. Autodesk offers a residency program in which participants from different academic and industrial backgrounds use the company's workspace, equipment and experience. There are similar centers in Boston, Toronto, and Birmingham. Automation is important but not dominant in these centers. They rely on technology to automate many tasks in design and prototyping, but product conception and design remain labor intensive. This involves the collaboration of interdisciplinary teams on solving problems and testing materials and product configurations. Also, many products require extensive post processing and manual inspection during prototyping and production. These centers handle a broad set of different projects ranging from robotics to fabrication and construction.

Several IDMFs work in cutting-edge innovative products, such as the manufacture of small satellites and rocket parts, and extra-planetary manufacturing, which requires the arrangement of complex circuitry and sensors, quality inspection and testing, and the handling of dangerous materials (e.g., nuclear material, propellants). Delft Aerospace Rocket Engineering (DARE), for example, has manufactured and launched several rockets successfully with help from their amateur community. DARE shares the specifications of their hardware and algorithms freely, and uses crowdfunding to finance their projects. The Israeli non-profit SpaceIL also manufactured and launched its first spacecraft to the moon via donations and volunteering.

3.4.3.2. Highly Automated, Closed Microfactories

These MFs are highly automated and have low levels of openness. They use their own engineers and in-house technology to manufacture products, which, due to 3DP and flexible robotics, can be highly customized. *Customization-driven MFs (CDMFs)* are predominant in this area. They seek to democratize product customization on an on-demand basis for local markets (Montes & Olleros, 2019). Adidas' Speedfactory Lab Experience and Nike's Makers Experience in the shoe industry, Gerber and AM4U in the apparel market and dozens of startups in the domain of 3D-printed biological implants, are good examples of this trend. They can all manufacture low-to-medium production volumes of highly customized, final products.

Although IDMFs and CDMFs share some common features (e.g., a relatively small physical footprint, small-to-medium-size production levels and on-demand fabrication for local markets) these two kinds of microfactories differ in important ways.

- While IDMFs often crowdsource new ideas and designs and use non-traditional ways to fund their projects, CDMFs use traditional sources of capital and don't generally thrive on external ideas and designs.

- While product design and prototyping are essential elements in IDMFs, CDMFs focus mostly on customizable but well-established final products and spare parts.
- While IDMFs serve mostly innovative industrial businesses, CDMFs serve mostly final customers.
- Although many of them are for-profit, IDMFs often have a culture of open design and can develop synergies with local entrepreneurial communities. Lacking this communitarian leaning, CDMFs are closed, self-contained shops.
- Like Fab Labs and makerspaces, IDMFs tend to combine a wide variety of machines and tools under the same roof. Instead, CDMFs tend to be highly automated and can be as small as a 3D printing station in a dentist's or retailer's back office.

Voodoo Manufacturing belongs to this type of highly automated, closed MFs. Voodoo hosts 160 3D printers assisted by robots, enabling both high customization levels and 24x7 production runs. Voodoo can process orders from one to 10,000 units and its printer farm is on its way to becoming completely autonomous.

Adidas' 'Knit for You' experience in Berlin can also be classified as a CDMF. The Knit for You makes personalized knitted sweaters to serve local markets. As customers enter the shop, scanners and sensors capture their body shape, customers then choose the color and material for their sweater, and press the "print" button, thus sending the captured model and preferences to machines that knit the sweater. The result is a garment that perfectly fits the shape of the customer and the process only takes four hours, as opposed to the many weeks or months of conventional fashion cycles. The process is highly automated and can take place at the point of sale. Knit for You was part of a 2017 research project between Adidas academic and industrial partners to test custom, on-demand, high-quality products made locally in a short period of time. In the same vein, Adidas Speedfactory relies mostly on 3D printers and robotic arms to produce shoes locally. Currently there are two such factories, in Ansbach, Germany and in Atlanta, Georgia, U.S., serving their respective local markets.

CDMFs can have high automation levels but some of the orders they receive require more interactions with customers and more manufacturing labor than others, depending on the complexity of the products, such as the case of Protolabs. As part of our experiential research, we tried to order a product from this firm. We noticed that we had to open an account in Protolabs and that its interface was less friendly than Voodoo's interface. Protolabs interface ("Dashboard") seemed to be for a more professional market segment and the prices were higher than Voodoo's prices. The company has several technologies (injection molding, overmolding, sheet metal fabrication, CNC machining and 3DP), not only 3DP as Voodoo does. Once we chose the technology (i.e., 3DP), we opened the account, selected the material (plastic) and the kind of plastic we wanted to use; there were 27 technical terms from which we had to choose, this hampered the selection. In the material selection page there was the option "Help me choose" and "I am not sure." The option "help me choose" was of little help, it opened a new window with more technical details. The option "I am not sure" did not provide an instant quote since a Protolabs' professional had to review the model to price it. After a few minutes, we learned how to use the dashboard, learned the basic properties of some printing materials, uploaded the model that we got from Thingiverse, chose the cheapest printing material (PA 12 Black), got the quote (64 USD), and selected a lead time of 3 business days (there were two options: 2 and 3 days); the faster the delivery, the more expensive. After that, we introduced the shipping and billing information. In the end, we did not complete the command because it was four times more expensive than in Voodoo manufacturing. The platform had the option "review quote" that we used to ask why the price was so high; a few days later a Protolab professional contacted us by phone with information about the model and why they were pricing it that way. Protolab's dashboard has more options and technical details (units, finish, quantity) than Voodoos' platform, this makes the dashboard (particularly the material selection page) less intuitive for an amateur but certainly more robust for an experienced designer.

3.4.3.3. Weakly Automated, Closed Microfactories

These machine shops (MSs) are mostly conformed by independent fabricators that provide low production quantities of highly customized products for different industries. The empirical exploration highlighted the importance of MSs, which we did not consider in our initial research assumptions. Unlike CDMFs, most of the MSs democratize manufacturing – not only product customization – and require high levels of human assistance in both, order intake and production. MSs can fabricate distinct products for a broad range of industries, but tend to specialize in low production runs of custom and complex products. They tend to focus mostly on industrial customers and business. The orders they handle are so complex that standard online forms are not enough to capture what customers want, so constant e-mails, calls and meetings may be needed for the firm and the customer to reach a consensus. The products or projects they develop require constant interaction with customers, given the heavy need for ideation, design, and redesign. Moreover, MFs in this domain rely on their own personnel for the design and manufacture of products, interacting heavily with individual customers, but never with an indefinite external crowd. They don't use crowdfunding or share information, designs and models freely. Independent fabricators such as FacFox, 3D ArcWest and Think 3D belong to this category. These are companies that offer 3D printing services along with 3D design, 3D scanning and in some cases CNC, injection molding and casting services. Despite their low levels of automation, many of these companies partner with MOMPs such as 3D Hubs, which help them find new customers, automate their order intake and provide insights to standardize production and increase quality. These companies are transitioning from hand-sketched concept designs to CAD and from traditional hand-made prototypes to 3DP to build prototypes, which facilitates the work and reduces time spent in making every item. However, the process of making some parts still require manual finishing. Via experiential research, we noticed that MSs exhibit various levels of development regarding their order intake. A couple of them had an automatic quoting system, and a sophisticated website to establish the printing parameters, pay and ship the product, but the majority of them only had a basic online form to fill out and a tab to upload the digital model. Most of the latter group lack automated solutions for price quoting, payments, and order tracking in real time.

In general, MSs do not have automated order-processing systems. *Addimen*, a firm that manufactures custom and complex products by using 3DP (hence facilitating automation), does not have a platform to handle orders automatically. The firm's personnel have to interact directly with customers to handle models with complex geometries that require extensive material and quality verification; hence, hampering order-processing automation. Moreover, Addimen sometimes needs to adjust, test and redesign products to meet its clients' expectations, making production automation difficult. Jewelry manufacturers such as *YC London*, *Isaac's Fine Jewelry*, and *Chandlers* also belong to this family of MSs. These companies are transitioning from hand-sketched concept designs to CAD and from traditional hand-carved waxes to 3DP to build prototypes, which speeds up the workflow. However, the process of making jewels still requires manual shining, polishing and setting of expensive stones in intricate and small size shapes. Personal communication with customers is key for them, as customers need to see the models, adjust sizes and choose the shapes and materials in which they want their jewels, hence face-to-face interactions are important. Moreover, choosing a product that someone is going to wear in very special moments, and perhaps for decades, makes frequent human interactions between customer and jeweler more necessary than for the manufacture of a spare part or a component of an engine.

3.4.3.4. Corporate and Independent MFs

Corporate MFs are usually affiliated with bigger corporations that provide financial resources, skilled labor, goodwill, technologies and an ample network of partners. Despite belonging to an umbrella firm, corporate MFs usually have the freedom to operate and grow on their own. For example, Launch Fourth, an IDMF, works closely with its parent firm Local Motors. Launch Forth leverages the power of its online community by designing and prototyping innovative products. Once this is done, Local Motors brings these products into small-scale production. Haiers' First Build and General Electric's Fuse are also good examples of corporate IDMFs. In the same vein, Factory in a Box, a CDMF, takes advantages of the experience in electronics and technological capabilities of its parent company, Nokia, to manufacture electronic components in a fully automated, modular and containerized factory. Adidas' Knit-for-you, Nike's Makers Experience and Gillette's Razor Maker are also representative of this group.

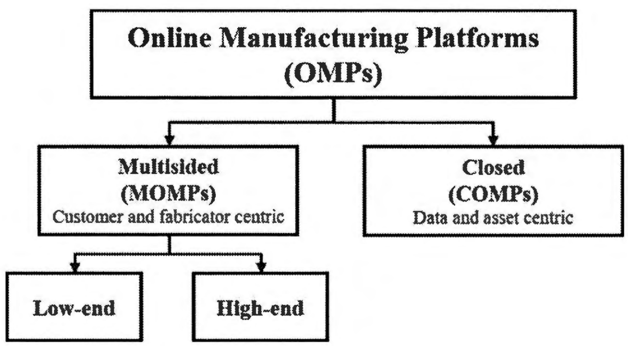
Independent MFs do not belong to larger firms; they are standalone firms that rely on their own financial resources, technologies and partners. For example, Kijenzi, a CDMF that 3D prints parts for medical equipment in Kenya, relies entirely on their founders, Dr. Gershensen and Benjamin Savonen, to raise capital and operate their 3D printers. As reported by Dr. Gershenson, the Kijenzi partners "have been trying to build their local network of 3DP, find partnerships with hospitals and 3DP developers" on their own.

Most of the MSs we identified are independent (e.g., FacFox, Think 3D, 3D ArcWest) and most IDMFs are corporate (e.g., Launch Forth, Fuse, First Built). CDMFs can be either corporate (e.g., Nokia Factory in a Box, Gillette Razor Maker, Adidas Made for You) or independent (e.g., Kijenzi, 3D Smile, Voodoo Manufacturing).

3.5. Empirical Findings about Online Manufacturing Platforms

Evidently, platforms and microfactories are two very different types of organizations. While the former work naturally in the virtual domain of services, the latter operate in the physical domain of products, they focus on manufacturing, and operate diverse and expensive technology. The data we gathered revealed that besides MOMPs, there is an additional type of platforms that we did not consider in our initial research assumptions, COMPs. As explained below, the data also show that two types of MOMPs, low-end and high-end, are quite different from each other (Figure 12). Some firms, such as Shapeways, have one part of their business multisided but not the rest of it.

Figure 12. Multisided and Closed Manufacturing Platforms



3.5.1. Multisided Platforms and Closed Platforms

Multisided online manufacturing platforms are lean operators that regulate and curate many aspects of online transactions, with a view to optimizing the connections and interactions between designers, makers and their final clientele. MOMPs are generally customer and fabricator centric: they leverage the fabricators' services and technologies and match them with the customers' requirements. Companies such as 3D Hubs, Xometry and Fictiv belong to this category.

Closed online manufacturing platforms, on the other hand, enhance the performance of major manufacturers by connecting, optimizing, virtualizing and scaling their own industrial installations. These platforms are usually owned by and serve large corporations. Closed platforms tend to be asset and data centric: they generate more value to firms that already possess large amounts of production assets. These platforms work by providing actionable and useful information from the data collected from these assets. ABB's Ability, Dassault's 3DExperience, General Electric's Predix, and Siemens' MindSphere, all of them owned by large Fortune 500 companies, are closed platforms. Predix, for example, is an asset centric, comprehensive platform that, based on GE's internal data and that of their clients, offers applications as diverse as predictive analytics, industrial monitoring, event management, and data visualization. While independent MSs need MOMPs to thrive, corporate CDMFs (e.g., Adidas' Knit-for-you) and IDMFs (e.g., Haier's FirstBuild) do not.

3.5.2. Low-end and High-end Multisided Platforms

During data analysis, we identified two types of multisided OMPs: *low-end* and *high-end.* (Table 13). Low-end online platforms connect all sorts of customers with curated and non-curated providers of manufacturing services. Aimed at democratizing access to manufacturing, they have a broad network of providers, many of them makers and hobbyists with a spare 3D printer at home. Many such providers lack industrial grade manufacturing technology, resulting in low-quality products offered at a low price. On the demand side, their customers tend to be a mix of hobbyists, students, and even some businesses with low expectations about product quality. PrintAThing and makexyz belong to this group of platforms. PrintAThing, for example, focuses on quickly and affordable manufacturing; it connects people with spare or unused home 3D printers with customers needing a printed product. Since their philosophy is based on a more "democratized 3D printing," providers need only meet a few basic requirements to post their services on the platform.

Table 13. Low-end and High-end MOMPs

Low-end platforms	High-end platforms
Available to an ample set of fabricators, many of them hobbyists	Open exclusively to experienced commercial fabricators with industrial grade technology
Available to a wide variety of customers, many of them hobbyists, but also some businesses and professionals	Mainly available to professional customers and businesses
Focus on accessibility and affordability of manufacturing services	Focus on quality, stability and reliability
Non-curated manufacturing technologies and services	Manufacturing technologies and services are curated by the platform
Fabricators do not require high quality, material and process certifications	High quality, material and process certifications are necessary

High-end platforms, instead, match professional and demanding customers with curated manufacturing services. These platforms focus on quality; they intend to guarantee the stability and reliability of the printed products; hence, they rely on commercial providers with ample experience in manufacturing. Such providers usually have expensive, industrial grade technology to manufacture premium products. Their customers tend to be businesses or professionals looking for high performance materials and products. A platform belonging to this group is Xometry. It connects demanding customers such as BMW, NASA, and General Electric with a network of 2500 local, highly vetted manufacturing providers with high-quality certifications. Xometry guarantees to its customers the manufacture of high-precision parts according to their specifications, regardless of the manufacturing technology used. ZVerse is another platform and designer marketplace optimized for the manufacturing-as-a-service (MaaS) ecosystem. ZVerse uses machine learning and a private network of expert 3D designers to offer an automated 3D Design Cloud. One interviewee from a well-known high-end MOMP emphasized to us that since most of their orders are generated by businesses, they need to focus exclusively on certified commercial providers.

MOMPs can migrate from the low-end to the high-end of the market as their business models evolve, and many of them have done so. In the past few months, 3D Hubs, a leading MOMP that used to cater to makers and their hobbyist clients, has severed its ties with such providers and customers to focus on better serving the high-end needs of business clients in the energy, medical, aerospace, defense and electronics sectors.

3.6. Discussion

Our empirical exploration corroborated some of our initial research assumptions, but it also provided new insights and challenged some of our premises. We were able to corroborate that IDMFs, CDMFs and OMPs are distinctive units in the emerging on-demand manufacturing ecosystem, as we had assumed. But we also came to realize the on-going importance of classic machine shops, that is, weakly automated independent fabricators using a broader set of manufacturing technologies and serving a more diverse array of industrial clients than IDMFs and CDMFs. This is something we had not anticipated.

We found that IDMFs tend to have relatively low levels of automation. The interviewees reported that, despite the increasing use of 3DP, generative design and virtual prototyping, the creation of new products requires constant trial and error, and manual circuitry/electronic arrangement, post-processing and finishing. For now, higher levels of automation in product development are not possible or even desirable.

We validated that IDMFs are more open to share their designs with an external community, more willing to open their shops to outsiders, and to leverage crowdsourcing platforms. However, the empirical data also showed that crowdfunding is less essential to IDMFs than we had initially assumed. Some IDMFs projects, especially those that emerge from entrepreneurial communities, do rely heavily on crowdfunding campaigns, but many others are backed by well-funded corporations.

The empirical findings were aligned with our initial assumptions that CDMFs do have high automation levels, do not share designs, do not open their shops to outsiders, and use neither crowdsourcing nor crowdfunding. But despite their high automation levels, for example, through heavy use of 3DP and automated chats, pricing and payments, CDMFs such as Protolabs and Voodoo still rely on backup human interaction for customers who need it.

The empirical exploration was especially useful in uncovering new insights about online platforms. We learned that the world of manufacturing platforms is more diverse and nuanced than we initially thought. Besides MOMPs, there are also closed platforms (COMPs), aimed at leveraging the data generated by corporate industrial assets. *We also noticed that there seems to be a strong symbiosis between MOMPs and independent fabricators, particularly classic MSs.*

Moreover, we identified two different types of MOMPs: low-end platforms matching non-curated fabricators with a broad set of customers, and high-end platforms matching exclusively premium manufacturing services with mostly professional customers. High-end MOMPs not only match customers with providers, as the literature on multisided platforms (Evans & Schmalensee, 2011) and matching markets (Roth, 2016) suggests; they also incentivize and help providers to keep upgrading the quality of their products and services. Via a stringent curation process, high-end MOMPs set technical and quality standards that providers must meet to guarantee a stable product that satisfies the requirements of the platform and the customer. Moreover, high-end platforms actively search for providers who have the technologies and capabilities requested by their customers and promote them among potential customers. In this way, they leverage both the supply and demand of high-quality manufacturing services. The director of supply of a large MOMP emphasized in their interview that education about emerging new solutions is key: "We educate the customers regarding the technologies that are available and their advantages."

Previous research has highlighted the cost advantages, modularity and flexibility of MFs (Montes & Olleros, 2019; Wells & Orsato, 2005). However, these advantages differ considerably across MFs and industries, especially regarding costs. In the electric vehicle sector, for example, the costs of setting up a MF are so high that many MFs struggle to find initial funding. One interviewee from an IDMF informed us that her factory was not yet profitable, the yearly operating costs exceeding 1 million dollars. "Feedstock and skilled people are expensive," she added. But in other industries the situation is less complex and costly. Thus, for example, setting up a production unit of dental aligners is less expensive, just a matter of obtaining the right 3D printer, modeling software, and dental planning tool.

In general, manufacturing is migrating towards more automation at the platform and factory levels. Generative design, virtual prototyping and testing, simulation of new material properties, and AI all push MFs (and some MSs) towards higher automation. Despite recent advances in embedded security, the trend may continue towards low openness to prevent security threats and ensure quality control.

Some companies that were born in the manufacturing domain started to develop systems to improve their own workflow and platforms to connect with customers. These platforms eventually became so useful that their owners turned them into standalone services offered to third parties. This is the case of 3D Smile, which saw a niche market for a seamless digital aligner workflow product, and began the production of its own specialized software solution. Currently, 3D Smile makes aligners but also offers a full IT design and workflow solution to other aligner manufacturers, typically dental labs or dental clinics equipped with their own 3D printers. Other companies have migrated completely from the fabrication sector to the online platform domain, such as On Demand Manufacturing Solutions (ODMS), which started as a MF but at the beginning of 2019 abandoned fabrication and turned into an online multisided business.

Several platforms seek to differentiate themselves from others by adding new services such as professional support in product (re)design and manufacture (e.g., material, printing technology and structural properties). Their modular software infrastructure allows them to keep adding new services with minimal overhead.

Independent MFs often rely on well-established multisided platforms such as Xometry to manage new orders and to connect with customers that they would otherwise have been unable to reach. Such matching platforms are invaluable for both customers looking for the right suppliers and fabricators looking for the right clients. Some of these platforms are still quite diversified on both sides of the market. But a trend toward privileging the high end of the market is starting to assert itself. Logically, industrial clients have little interest in doing business with amateur fabricators.

We also found some fabricators with highly automated and robust in-house platforms to manage their own orders and manufacturing processes, such as Protolabs, which has an automatic quoting and order-tracking system. But such automated capabilities are not easily applicable across the board. For certain products, the whole process (from order to shipping) can happen with minimal human intervention. But for more complex products and transactions, human intervention remains necessary. Going forward, as generative design and virtual prototyping and testing become more powerful, as monolithic design and printing become more widespread, and as flexible robots acquire better finishing capabilities, many more fabrication tasks will be automated.

In different ways, IDMFs and CDMFs enable transformative business models that were not previously viable. Thus, while the IDMF enables the gradual, risk-free scaling of new products from prototype to mass market, the CDMF enables the on-demand offering of low-cost customized products in local markets. Consequently, while IDMFs could boost the pace of innovation across all sectors, CDMFs may lead to extensive reshoring and the collapse of global value chains in markets characterized by heterogeneous and fluid demand preferences. Export-driven countries with abundant low-cost labor are likely to be the most negatively impacted by such changes.

Experts seem to agree that future corporate factories will be increasingly automated and connected not only to one another but also to their clients' products (e.g., airplanes) and installations (e.g., power plants) at all times. In this 'Industrial Internet of things' vision, sophisticated software platforms will manage such hardware networks in real time, transforming the world of fabrication just as algorithms and big data are transforming the world of services (Bolz, Freund, Kasah, & Koerber, 2018). There is however, no consensus as to the consequences of such trends concerning firms' scale and industry concentration. Thus, while many authors maintain that the rise of 3DP and software platforms will lead to more decentralized industrial ecosystems (Diez (2016); Gershenfeld et al. (2017), Richard D'Aveni claims that the combination of the scale economies enjoyed by software platforms and the scope economies of increasingly powerful additive manufacturing will power the rise of a few global pan-industrial firms (D'Aveni, 2018). In this paper, in tune with Mayer-Schönberger and Ramge (2018), we argue that decentralizing forces can only prevail to the degree that multisided online manufacturing platforms (e.g., 3D Hubs, Open Desk) manage to partner with and revitalize the world of independent local shops and microfactories.

3.7. Conclusion

Based on a multiple case study, this paper has tried to explore, contrast and classify different on-demand manufacturing firms and platforms. We used data from the Internet (websites, magazines, newsletters, videos and blogs) complemented with interviews, experiential research, and virtual or physical tours of platforms and factories. From August 2018 to April 2019, we explored 71 cases (61 microfactories and 10 platforms) in 21 different countries and in several manufacturing industries: electronic, machinery and equipment, motor vehicles, pharmaceutical, spacecraft, and clothing.

To answer our first research question – *What are the different types of MFs currently operating and how can we best classify and compare them?* – we developed a taxonomy of MFs with two dimensions: *automation* and *openness*. Automation is indirectly measured by the level of human involvement in both order intake and manufacturing; it can range from low to high. Openness is measured by the extent to which MFs collaborate with a broad and diverse community, receive funding via non-traditional ways, and facilitate the free flow of designs; MFs range from closed to open. The taxonomy suggests that there are three distinct types of MFs: innovation-driven microfactories (IDMFs), customization-driven microfactories (CDMFs) and classic machine shops (MSs). IDMFs exhibit low automation and high openness levels; they aim to reduce the risks and cost of innovation by enabling gradual scalability in new product launches. CDMFs exhibit high automation and low openness levels; they seek instead to democratize product customization on an on-demand basis and focus on a narrow set of products and industries. MSs exhibit low automation and low openness levels; they aim to democratize manufacturing, and have the capabilities to manufacture a very broad range of products for different industries. We also found a difference between *corporate* and *independent* MFs. Corporate MFs are affiliated or belong to corporations that provide financial resources, skilled labor, goodwill, technologies and an ample network of partners. Independent MFs are standalone firms that have to leverage their own financial resources, technologies and partners. Most MSs are independent, most IDMFs are corporate and CDMFs can be either corporate or independent.

To answer the second research question – *What are the different types of online manufacturing platforms currently operating and how can we best classify and compare them?* – we developed a conceptual framework about manufacturing platforms. The framework suggests that closed online manufacturing platforms (*COMPs*) are very different from multisided online manufacturing platforms *(MOMPs)*. Closed platforms enhance the performance of major manufacturers by connecting, optimizing and scaling their own installations and those of their industrial clients. Such platforms tend to be asset and data centric and are usually owned by large corporations. Multisided platforms on the other hand, are customer and fabricator centric, tend to be lean operators who regulate and curate many aspects of the transactions, and generally focus on connecting independent fabricators with their final clientele.

We also found important differences between *low-end* and *high-end* MOMPs. Focused on democratizing the access to manufacturing facilities, low-end platforms connect all sorts of customers (from amateurs to professionals) with curated and non-curated fabricators. Focused on quality, *high-end platforms*, match instead professional customers with highly curated manufacturing services. Unlike the former, the latter are actively invested in helping both sides of the market to track and exploit the latest technologies (e.g., new designs, hardware, software and materials for additive manufacturing) and their best practices. As this divergence becomes amplified with time, amateur makers will become increasingly marginal, as their best tools and practices will not be comparable to those of industrial suppliers.

In regards to our third research question – *To what degree and in what conditions do MFs and multisided platforms need each other to survive and thrive?* – currently, there are two opposing views about the likely future of manufacturing. On one side, Richard D'Aveni, from Dartmouth College, claims that global manufacturing will soon be dominated by a handful of pan-industrial corporations, whose tightly integrated networks of flexible factories will leave little room for small manufacturers (D'Aveni, 2018). On the other side, MIT's Neil Gershenfeld claims that the future of innovative manufacturing will be local and distributed. In his view and that of hundreds of proponents of Fab Labs and other makerspaces, while mass manufacturing will not disappear, innovative fabrication projects will increasingly be found in local communitarian initiatives (Diez, 2016, 2018). So far, 28 cities across the globe (including Boston, Paris and Barcelona) have committed themselves to manufacturing all the products they will need by the year 2054 (Diez, 2018; FabCity, 2019).

We suggest that these two views need not be mutually exclusive. In a manufacturing world increasingly managed by digital platforms, both giant pan-industrials (with their own in-house platforms) and smaller entrepreneurial firms (connected to multisided platforms) can coexist and innovate, competing to some extent but also complementing each other. While closed platforms will enhance the performance of major manufacturers (cf. D'Aveni, 2018), MOMPs can give independent MFs the chance to thrive alongside the giants (cf. Ben-Ner & Siemsen, 2017; Mayer-Schönberger & Ramge, 2018). Due to OMPs, both D'Aveni (on the giants' side) and Ben-Ner & Siemsen and Mayer-Schonberger & Ramge (on the side of small fabricators) could be right in their respective predictions. A strong symbiosis between MOMPs and independent MFs would profit both.

On-demand manufacturing services and multisided manufacturing platforms have boosted the long tail of products. The design and fabrication of a much larger array of products is becoming economical.

In this paper, we have provided a simple conceptual framework to classify MFs and OMPs. Future research can focus on developing more accurate measures of openness and automation, providing additional dimensions to better classify MFs and OMPs and selecting more optimal strategies for each type of player in the on-demand fabrication ecosystem.

The results presented here amount to a snapshot of a very fluid ecosystem, at a given point in time. Hence, as further technological and business model shifts occur, new types of MFs and OMPs may appear or the current ones may need to be classified differently. Some important questions remain open. How strong is the trend towards distributed local fabrication (Waldman-Brown, 2016a)? To what extent can decentralized technologies enable sustainable futures for value creation (Waldman-Brown, 2016b)? To what extent will large, vertically integrated pan-industrial firms dominate Industry 4.0 (D'Aveni, 2018)?

3.7.1. Implications for Businesses

The trend towards higher levels of automation for platforms and factories remains steady (Edlich, Ip, Panikkar, & Whiteman, 2018). At the platform level, both COMPs and MOMPs are highly automated. It makes little sense to do the matching work between customers and fabricators manually, especially in a dynamic market in which technology, manufacturing materials, customers, providers and product configurations constantly change and upgrade. Platform-based companies are working hard in automating the remaining tasks that are carried out manually. At the fabrication level, automation keeps improving and spreading: robots, 3DP, generative design, AI and automatic quoting algorithms, are indicative of these trends. Firms that do not adapt to these best practices will sooner or later become uncompetitive.

The combination of high openness and high automation seems to be a no-go zone for MFs, at least for now. Companies that invest millions of dollars to automate their processes and order intake can generally count on brilliant people to design their products in-house. These companies are generally well established and aim to scale manufacturing rather than constantly innovate and launch disruptive products. Consequently, they do not need to be wide open to external ideas. Meanwhile, at the platform level, profitability and high quality do not necessarily go well with democratization. Low quality and low-cost manufacturing is not profitable enough to sustain MOMPs burdened with high fixed costs for servers, engineers and installations. Not surprisingly, most of them are trending toward offering highly reliable services for industrial clients.

Our analysis shows that online platforms (be they closed or multisided) are becoming core elements of on-demand manufacturing ecosystems across the world. As 3D Hubs' recent business-model pivot highlights (Boissonneault, 2018), there are strong incentives for the best platforms to migrate toward the high end of the market, thus abandoning their hobbyist clients. Since platforms are rich in network effects, the relative performance of high-end professional platforms and low-end amateur platforms will tend to diverge increasingly fast. Consequently, there will soon come a time when, unable to team up with leading-edge platforms, amateur maker shops will not be able to compete with their professional counterparts. As the offer provided by industrial-grade service bureaus keeps improving in quality and affordability, even amateur designers will have nothing to gain from choosing amateur makers over such service bureaus.

3.7.2. Implications for Theory

In a connected age, the sharing of resources, even physical ones, becomes easier and more compelling. Moreover, such sharing need not be communitarian: new sharing-based markets and business models can become possible and optimal (Benkler, 2007; Sundararajan, 2016). In this context, it is not surprising to find that the degree of openness has become a central dimension for both MFs and manufacturing platforms. But our analysis shows that there are several different aspects and dimensions to openness. In the world of MFs, openness has to do with both the free access to proprietary tools and designs enjoyed by an external community and the access to external funds, designs and ideas enjoyed by a firm. In the world of OMPs, on the other hand, openness has mainly to do with free access through a digital platform to the other side of a market, by periphery players, be they designers, fabricators or final clients.

Our analysis also shows that while in the world of IDMFs openness to external funds, designs and ideas may have its advantages when it comes to innovation, it rarely is an imperative for MSs and CDMFs. Contrarily, the widely-shared use of a common transactional infrastructure is an imperative for the survival of MSs and OMPs alike. In our view, going forward, a symbiotic relationship with vibrant open platforms is the only realistic option for small fabricators hoping to compete with major incumbents.

CONCLUSIONS

The research here presented responds to the need to understand the business model transformations and manufacturing changes facilitated or imposed by some emerging technologies and online platforms. The central theme of this study focuses on the business models and manufacturing dynamics enabled by digital manufacturing technologies—notably, 3DP—and online manufacturing platforms. This theme is part of the broader emerging field of Industry 4.0, which integrates transformations at the technology and manufacturing level allowing higher levels of automation and operational efficiency. Emerging technologies such as additive manufacturing have the potential to disrupt supply chains and change the way products are designed, fabricated and distributed. However, for optimal impacts, such new technologies need to be accompanied by appropriate business models and strategies.

This study explores three elements of the Industry 4.0 domain: technologies and business models, manufacturing configurations, and online manufacturing platforms. Regarding the first element, technologies and business models, the first chapter explores how 3DP is impacting the development of new business models. While there is abundant research on the technical aspects of 3DP and on its general influence on manufacturing, there is less research on how this technology affects new and existing firms. By means of a multiple case study, involving 25 Colombian firms, the results of the first chapter show that new firms and business models are indeed being created with 3DP as a central element. In the medical industry there are firms creating custom implants based exclusively on additive manufacturing, in the art industry there are firms developing plastic replicas (although they manufacture replicas, they consider themselves as artists) of humans and animals by using 3DP, in the tool sector there are manufacturers of 3DP kits, and so on. The interviewees report that this technology has allowed them to make custom products in a cheaper, faster, and more efficient way. Moreover, additive manufacturing is affecting the business models of existing firms. 3DP allows some firms to increase their value proposition by saving time and money to customers, improve the value creation by reducing the use of resources and processes in manufacturing, and accrue the value communication by facilitating the visualization of products beyond a CAD model. Furthermore, the impact of 3DP is not even across all firms. While in some firms 3DP is part of the central business and affects manufacturing broadly, in others the impact is marginal. The notions of technology and service complementarity also emerged from the results. Technological complementarity refers to the right mix of technologies a firm should have to increase its value creation; service complementarity is related to the new services that complement a firm's existing services to increase the value proposition of the whole business, attract more customers, and make the firm more profitable.

Regarding the second element, manufacturing configurations, the second chapter explores the microfactory model. Firms usually spend large amounts of money when launching new products, without knowing with any certainty whether the new offers will be accepted by the market. Such risky bets are a problem that innovative firms have to frequently face; the microfactory model represents a possible solution. The chapter argues that MFs may indeed reduce the costs and risks of innovation, while enhancing local on-demand fabrication, and filling the gap between artisanal and mass production processes. MFs allow firms to develop and fabricate new products and test their acceptance in local markets before deciding to mass-produce them.

With regard to the third Industry 4.0 element, online manufacturing platforms, chapter three explores the evolving symbiosis between these platforms and microfactories. While some scholars argue that manufacturing will soon be dominated by a few large, vertically-integrated and cross-sectoral corporations leveraging massive economies of scale and scope (D'Aveni, 2018), others argue that manufacturing is on its way to becoming more localized and distributed (Gershenfeld, 2012; Mayer-Schönberger & Ramge, 2018). By means of a taxonomy that emerges from a multiple case study of 71 firms across the world, chapter 3 argues that there is room for both large corporations and smaller independent fabricators to thrive. However, the success of the latter will depend on the symbiosis they create with online manufacturing platforms. The taxonomy suggests that automation and openness are key dimensions of MFs. According to the empirical taxonomy, three kinds of MFs coexist: factories with low automation and high openness levels, which tend to be IDMFs aimed at reducing the costs and risks of innovation; factories with high automation and low openness levels, which are generally CDMFs seeking to democratize product customization on an on-demand basis and in a narrow set of products and industries; and factories with low automation and low openness levels, which tend to be MSs aiming to democratize manufacturing, with a very broad range of products catering to various industries. MFs can also be corporate—belonging to large corporations—or independent—standalone firms that have to leverage their own resources and partners.

Relative openness is also a differentiating dimension for online platforms. They can be closed online manufacturing platforms (*COMPs*)—which are asset and data centric, and are usually owned by large corporations to enhance the performance of their own installations and equipment—and multisided online manufacturing platforms *(MOMPs)*—which are customer and fabricator centric, are lean operators who regulate and curate many aspects of market transactions, and generally focus on connecting independent fabricators with their final clientele. MOMPs, in turn, can be *low-end* and *high-end*, depending on the market segments that they cater to.

This research makes four main contributions. First, it provides empirical evidence on how emerging technologies, such as 3DP, affect business models, the development of new firms and manufacturing dynamics. Second, it explores the interplay between online manufacturing platforms and microfactories and offers a way to classify and contrast them, which may help us to better understand the reality and potential of local on-demand fabrication. In turn, a better understanding of the features of the different types of on-demand fabrication approaches should enable better strategy, evaluation and policy choices. Third, it highlights some features not discussed in prior scholarly literature on MFs and provides an in-depth analysis of how distinct digital manufacturing technologies can alter how products are developed, financed, and made. Fourth, this research introduces a novel form of experiential research, in which we observe first-hand the interactions of a firm with its customers, thus allowing us to develop a richer interpretation of the firm than would be possible via interviews, secondary sources and netnography alone.

ANNEX

ANNEX A: Keywords Scientific Literature

Database	Research string (Research, September 09, 2018)	Number of documents	References after deduplication
Scopus	TITLE-ABS-KEY ("on-demand fabrication" OR "on demand fabrication" OR "on-demand manufactur*" OR "on demand manufactur*" OR "on-demand production" OR "on demand production" OR "mass customization" OR "local value chain") AND DOCTYPE (ar)	1962 document results	1760
Proquest (ABI/Inform)	noft("on-demand fabrication" OR "on demand fabrication" OR "on-demand manufactur*" OR "on demand manufactur*" OR "on-demand production" OR "on demand production" OR "mass customization" OR "local value chain")	286 results	118
Ebsco (All databases,	"on-demand fabrication" OR "on demand fabrication" OR "on-demand manufactur*" OR "on	941. I could only import 583 to EndNote	347

English, full text, peer-reviewed)	demand manufactur*" OR "on-demand production" OR "on demand production" OR "mass customization" OR "local value chain"		
WoS (from All Databases)	TOPIC: ("on-demand fabrication" OR "on demand fabrication" OR "on-demand manufactur*" OR "on demand manufactur*" OR "on-demand production" OR "on demand production" OR "mass customization" OR "local value chain") Refined by: LANGUAGES: (ENGLISH) AND DOCUMENT TYPES: (ARTICLE) Timespan: All years. Databases: WOS, CCC, DIIDW, KJD, MEDLINE, RSCI, SCIELO. Search language=Auto	1666	908

ANNEX B: Keywords for Firm's Identification

English	French	Spanish
micro-factor*	micro-usin*	micro fabrica*
microfactor*	microusin*	producción bajo pedido
micro factor*	micro usin*	producción bajo demanda
on demand manufacturing	manufacture sur demande	fabricación bajo demanda

on-demand manufacturing on demand fabrication on-demand fabrication on-demand production on demand production make to order mass customization cloud manufacturing additive manufacturing 3D printing Manufacturing as a service platform as a service Manufacturing as a service	fabrication sur commande fabrication sur demande fabrication à la demande production à la demande personnalisation de masse	manufactura bajo pedido

ANNEX C: Interview Guide

Interview No.			
Date		**Place**	
Interviewed		**Occupation**	
1. Introduction (about 3 minutes)			
a. Thank the interviewee for his or her time			
b. The information gathered will be used to better understand local on-demand fabrication initiatives and classify them. The hope-for result is an article in an academic journal. Any sensitive part of information gathered will be analyzed in an aggregated way to guarantee anonymity and confidentiality. Moreover, the information you provide will be used only for academic purposes. Do you agree that I record this interview? Do you have any questions before we start?			
c. Can you tell me about your role in the firm? Probe: job, experience			

2.	Asking for missing information (about 10 minutes)
a.	Can you tell me more about what your firm does and the services it offers? Probes: manufacturing, design, intermediation, a mix of them
b.	Can you tell me about the technologies you use? Probes: examples of technology, usage, quantity and frequency
c.	Can you tell me about the levels of involvement of the workers in the processes? Probes: degrees of automation
d.	Can you tell me about the market you serve? Probe: local, regional, national or international market, share of the market, industry they serve.
e.	Can you tell me about how you fund your projects? Probe: crowdfunding.
f.	Can you tell me about the customers' involvement in your innovation processes? Do you share designs freely? Probe: crowdsourcing, openness
g.	Can you tell me about how open your facilities are to external makers? Probe: Open shops.
3.	Digitalization, speed, customization and defies (about 10 minutes)
a.	Can you tell me about the role that digitalization plays in your firm? Probe: digitalization, relevance of digital processes, intensity.
b.	Can you tell me about how fast you serve your various customers? Probe: production speed, design speed, intermediation speed.
c.	Can you tell me about the range of products you manufacture? How frequently and in what volumes? Probe: customization, frequency, production volume.
d.	Can you tell me about the challenges your firm experienced during its founding and how you addressed them? How about the challenges that you face now and how do you address them? Probe: challenges and solutions
4.	Closing questions (about 5 minutes)

a.	What do you think should be done at the policy level to strengthen on-demand fabrication initiatives? What further technological or economic research needs to be done?
b.	What technology do you currently use more (e.g., AI, 3DP, IoT, virtual prototyping, etc.)? What changes have had more transformative impact in your business model, and why? What changes will have more transformative impact in the next 20 years, and why?
c.	What do you think about the future of manufacturing (probe: Large Pan-industrials (D'Aveni), small production units or Fab Labs (Neil Gershenfeld), or an intermediary option?)
d.	Do you have any further comments related to on-demand fabrication?
5.	Closure (about 2 minutes)
a.	Thank the interviewee
b.	This exercise is an important contribution to my research
c.	May I contact you for further information, or for a future interview?

ANNEX D: Independent Magazines and Websites

Magazines
https://compassmag.3ds.com/
https://3dprintingindustry.com/
http://producersoftomorrow.economist.com/
https://www.digitalistmag.com/
https://www.textileworld.com/
https://www.manufacturingtomorrow.com/
http://www.digitaljournal.com/
https://www.environnement-magazine.fr
https://www.modaes.es/
https://www.tctmagazine.com/
http://amtil.com.au/
https://www.electronicdesign.com/

https://www.manufacturingglobal.com/magazine
https://3dadept.com/magazine-3d-adept-mag-fr/
https://www.wired.com/
https://techcrunch.com/
https://newatlas.com/
https://www.aerospacemanufacturinganddesign.com/
https://qz.com/
https://www.designboom.com/
https://www.economist.com/
https://3dprint.com/
Websites
https://www.bloomberg.com/canada
https://www.glassdoor.ca/index.htm
https://singularityhub.com/
https://www.bbc.com/
https://www.engineering.com/
https://www.piworld.com/
https://www.lesechos.fr/
https://crnnoticias.com/
http://news.mit.edu/
https://www.mfg.com/discover/
https://www.bizjournals.com
https://www.financialexpress.com/
https://www.makepartsfast.com/
https://www.7x7.press/
https://www.larecherche.fr/
https://www.lecho.be
https://es.fashionnetwork.com
https://www.diariodeleon.es/
http://www.cao.fr/
https://www.3dprintingbusiness.directory/

https://www.crunchbase.com/
https://www.leblogauto.com/
https://www.youtube.com/
https://www.americamakes.us/
https://fashionunited.info/
https://spacenews.com/
https://www.space.com/

APPENDICES

APPENDIX A: Interview Guide Impacts of 3DP on Business Models (Chapter I)

Interview No.			
Date		**Place**	
Interviewed		**Occupation**	
6. Introduction			
1. Thank you for your time.			
2. The information will be used to understand the impacts of 3D printing (3DP) on the development of new business models. The outcome is a journal article. The data will be analyzed in an aggregated way to guarantee anonymity and confidentiality. Moreover, the information you provide will be used for academic purposes. Do you have questions before beginning?			
7. Context, business and technology related questions			
(Note: Ask for examples, facts, recent real situations, ask the same question in other ways to verify answers. Modify slightly the questions depending on the informant, the context, and the business). 1. Could you talk about your training and university from which you graduated? 2. Could you talk about your work experience and years of experience? 3. Could you talk about the first time you saw a 3D printer? 4. Could you talk about the history of company? 5. Could you talk about the technologies you have in your company? 6. Could you talk about the first printer you purchased? 7. And the price? 8. Could you talk about your sales volume? 9. Could you talk about the services offered by your company?			

10. Could organize these services from the more profitable to least profitable?
11. Could organize those services from the most important to you in terms of sales volume, profitability, and future potential?
12. Could you talk about the products sold by your company?
13. Could you talk about the products you manufacture more?
14. Could you talk about the reasons for you to buy this technology?
15. Could you talk about the reasons for you to get into the business of 3D printing?
16. Could you talk about your competitors?
17. Could you talk about your relationship with customers?
18. Could you talk about the profile of your customers?
19. How do you contact them?
20. Could you talk about the profile of the people working with you?
21. How many employees are there?
22. What age range are your employees?
23. Is your company profitable?
24. Could you talk about it?
25. What they are the main sellers of 3D printers and 3D services?
26. Could you talk about how 3DP meets the needs of the industry?
27. What industries have decided to have their own 3D printing system in house?
28. Could you talk about your relationship with suppliers?
29. Who are your suppliers? From which countries are they?
30. Could talk about your relationships with other institutions?
31. Could you talk about your alliances?
32. Could you talk about the influence of 3D printing on the development of new business models and new businesses?
33. How 3D printing has affected your business?
34. How has it affected your relationship with customers?
35. What makes it different 3D printing from other technologies other?
36. Could you talk about how 3D printing is affecting your sector?
37. Could you talk about how 3D printing is affecting the economy in general?
38. Could you talk about the negative consequences of 3D printing?

39. Could you talk about what should be improved on 3DP technologies? 40. What do you think should be done at the policy level to foster 3DP? 41. Is there any other topic not find discussed in this interview that seems relevant?
8. Effects of 3DP on the development of (new) business and business models
1. Can you talk about the effects of 3DP on your enterprise? Probe: what areas and processes are affected by 3DP and how 3DP has changed the way you get your revenues and satisfy your customers, or have helped you to develop a whole new business model?
Can you talk about how 3DP is affecting the creation new ways to satisfy the customers' needs? 2. Could you talk about if/how 3DP is leading to the development of new business models? 3. Which functional areas are affected most? 4. Could you talk about how these areas and processes are affected by 3DP? Probe: Value proposition (offering and target customers, job to be done)
5. Can you talk about how 3DP is creating new sources of revenue in your company? Probe: Value capture (revenue model, cost structure, resource velocity – inventory, assets).
6. Can you tell me how 3DP is affecting the operational and managerial processes that allow the creation of new products? Probe: Value creation: Key processes (design, development, manufacturing, marketing), rules, metrics, and norms, that make the profitable delivery of the customer value proposition repeatable and scalable. Resources (people, information, technology, equipment, brand).
7. Can you about how 3DP is affecting the way you deliver products to your clients? Probe: value distribution (channels, partnerships, and alliances).
9. Closure
1. Thank you very much for your time.
2. This interview provided important information to my research.
3. May I contact you for further information or for a future interview?

APPENDIX B: Quotations by Code by Type of Enterprise (Chapter I)

		Providers of 3DP Services											Product developers					Makers				End product manufacturers			Distrib utors	In-house protot yping	
No	Codes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	TOTALS:
2	Acreditations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
4	Alliances	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	2
5	Automatization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
6	benefits	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
9	Channel -	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
10	Closed at the begin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
11	Cocreation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	0	0	7
12	Communication	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3
13	Community buildin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
14	Complexity	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	2
15	Complexity reducti	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3
17	Continuous dialogu	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	4
19	Core business	0	3	7	4	4	2	2	0	1	1	1	3	1	5	2	1	2	3	4	3	1	3	2	2	1	58
21	Creation of new bu	1	0	1	0	3	0	1	1	0	0	0	0	0	2	0	0	1	0	0	0	1	7	3	2	0	23
22	Customer profile	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
23	Customization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3	0	2	0	6
24	Demand pull	0	0	0	0	1	0	0	0	0	0	0	0	1	0	2	1	0	0	0	0	0	0	0	0	0	5
25	Demonstration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
26	Design	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2
27	Development	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	2	5
28	Diversification	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	0	2	0	0	0	0	0	1	0	0	8
31	Drivers of technolo	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3
32	Easy than before	0	1	0	0	1	1	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	3	0	0	0	9
33	Effect of 3DP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	4	0	5	19
34	Employees	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2
35	Enterprise history	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	4
36	Experience	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	7
38	Flexibility	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	4
40	Functionality	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	3
44	Guarantee	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
45	High Cost of techno	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
46	Hobbist	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
49	Increased sales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2
50	Innovation	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	4	2	0	0	8
52	Lack of knowledge	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
53	Less material waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
54	less people	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	4	7
55	Less processes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	4	6
56	Less time	0	4	4	0	3	3	1	0	0	0	0	1	0	5	3	0	0	1	0	1	0	5	4	1	3	39
57	Low cost	0	4	1	0	3	3	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0	2	5	1	0	26
59	Low Inventory	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2
60	Low reliability	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
61	Low revenue	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
62	Management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2
63	Market	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
64	Marketing	0	0	3	2	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2	1	1	13
68	New Business Mode	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	6	2	0	0	13
69	New marketing pro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	3
71	No affects value co	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
72	No affects value dis	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3
73	No New Business M	1	0	0	1	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	1	7
74	Novelty	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	4
75	Number of employe	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	6
76	Operations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3

		Providers of 3DP Services											Product developers					Makers				End product manufacturers			Distrib utors	In-house protot yping	
No	Codes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	TOTALS:
77	People impressions	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
78	People training	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	3
79	Physical object	2	0	1	0	1	2	1	2	0	0	0	0	1	1	0	1	1	0	0	0	0	0	1	0	7	21
81	Planning beforehan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	2
86	Problem solving-pr	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2
87	Problems of techno	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
89	Profession	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	4
90	Prototyping	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	1	5
91	Quality	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	5
93	Rentability	0	0	0	0	1	1	1	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	1	0	0	7
94	Research	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	0	0	6
95	Revenue model	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	3
97	Service complemen	7	1	1	0	4	0	1	7	1	1	1	0	3	1	1	3	1	0	0	0	0	1	0	0	1	35
98	Services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	2
100	Strong Relations wi	0	0	1	1	0	2	0	0	0	0	0	1	1	0	1	1	0	2	1	2	1	5	3	1	0	23
101	Technologies used/	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	2	0	0	0	0	0	0	5
102	Technology comple	4	1	1	0	6	0	1	4	1	1	1	0	5	0	2	5	1	0	1	0	0	1	0	1	0	36
105	Time of printing	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
106	Traditional Marketi	1	0	0	0	1	1	0	1	0	0	0	0	1	2	1	1	1	0	0	0	1	0	0	0	0	11
107	Trained salesperson	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	4
108	Transformation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	5
109	Trial and error	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	3
110	Try before mass pro	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	2	6
111	Value capture	1	0	1	0	0	0	0	1	1	1	1	0	0	2	1	0	1	0	1	0	0	5	1	1	0	18
112	Value communicati	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	2	6
113	Value communicati	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	3
114	Value Creation	1	1	8	2	4	3	2	1	1	1	1	2	7	6	5	7	6	2	3	2	1	8	7	5	6	92
115	Value creation in er	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	7
116	Value distribution	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	1	0	1	0	0	3	0	0	8
117	Value propositon	3	5	9	2	3	2	0	3	1	1	1	2	7	4	2	7	6	1	1	1	1	7	4	4	6	83
Total		47	24	42	12	40	24	15	47	7	7	7	14	33	41	28	33	45	13	14	13	10	106	93	40	56	811

APPENDIX C: Coding Schema: Example of Analysis and Grouping (Chapter I)

Quotation	First order concepts	Second order themes (Business model components)
"The fact that you do not have to create a mold to make something custom and that you can do it neatly from a digital file and that you can print it once it is digital represents a very high gain" (Carlos) "Recently we are developing a Drone ... this is the first Drone we are doing by ourselves. We are doing here some pieces of the engine with highly resistant components." (Andrés Henao from 1/4TECH Maker Space)	Product offering: new technology	Value proposition
"Make-R is a company that was born and I see as an option to promote technological development in Colombia and in the region—in Latin America—through education." (Carlos)	Service offering: Education and training	

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