LOCAL ON-DEMAND FABRICATION: MICROFACTORIES AND ONLINE MANUFACTURING PLATFORMS

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Purpose: This article explores a particular on-demand fabrication unit, the microfactory (MF). It identifies and contrasts several MFs and proposes a taxonomy. This research also explores online manufacturing platforms (OMP) that complement certain MFs.

Methodology: This research implements a multiple case study (71 cases in 21 countries), triangulating data available on the web with interviews, virtual/physical tours, and experiential research.

Findings: The results suggest that automation and openness are the main dimensions that differentiate the MFs. Using these dimensions, a taxonomy of MFs is created. MFs with relatively low automation and high openness tend to be innovation-driven microfactories (IDMFs). MFs with high automation and low openness levels tend to be customization-driven microfactories (CDMFs). And MFs with relatively low automation and low openness tend to be classic machine shops (MSs). There are two types of OMP, closed (COMPs) and multisided (MOMPs). MOMPs, in turn, can be low-end or high-end.

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Practical implications: In a world where online platforms are becoming central to the reinvention of manufacturing, multisided online platforms and small fabricators will become strongly symbiotic.

Originality: This paper offers a clearer conceptualization of MFs and OMPs, which may help to better understand the reality of local on-demand fabrication. Moreover, it explores a new type of experiential research, which tries to better understand firms through the researcher's involvement in transactional activities. Some details of a firm that are difficult to capture via interviews and netnography can be revealed this way.

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

1. Introduction

The synergy between new technologies and online platforms is changing the manufacturing landscape and is facilitating local on-demand production (Hagel, Brown, Kulasooriya, Gif, & Chen, 2015; Waldman-Brown, 2016a). Several large companies are already working toward a more local on-demand production enabled by powerful platforms: 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 microfactories (MFs) – fabrication units optimized for the small-to-medium-scale manufacture of a variety of products (Montes & Olleros, 2019) - and online manufacturing platforms –virtual hubs that connect firms or people needing to make a part or a prototype with potential suppliers. We classify and contrast several MFs and manufacturing platforms highlighting their diversity, similarities and complementarities by means of a taxonomy and a conceptual framework.

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 and experiential research to answer these questions. The latter consisted in 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.

This study makes several theoretical, practical and methodological contributions. At the theoretical level, it reassesses the received wisdom about microfactories (MFs) and online manufacturing platforms (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, it offers a better understanding of the advantages and disadvantages of the various types of on-demand fabrication approaches as enablers of 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 obviate 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 innovation-driven microfactories (IDMFs), the second ones are customization-driven microfactories (CDMFs) and the third ones are classic machine shops (MSs). 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. 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 and streamline 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 ('panindustrials', as Richard D'Aveni (2018) calls them), the rise of MOMPs should enable the growth and success of independent fabricators. Thus, going forward, it should be possible for independent fabricators to thrive in a world of panindustrial giants, but only if they team up with leading-edge MOMPs.

The remaining sections are structured as follows: section 2 surveys the on-demand fabrication and platform literature; section 3 offers a detailed explanation of our research methodology; section 4 presents the empirical findings; section 5 discusses our results and section 6 concludes the paper.

2. Literature Review

2.1. Microfactories

The term MF can refer to both *miniaturized factories* that manufacture very small products and *decentralized production units* for on-demand fabrication of products of any size. In the case of miniaturized factories, a MF tries to fit manufacturing systems to the small size of the parts they produce (Okazaki, Mishima, & Ashida, 2000). Kawahara et al. (1997) identifies two types MFs: fabrication by desktop factory and fabrication by small robots. While the former are desktop factories that can be distributed in various places, the latter based on a group of several micro robots that cooperate to carry out certain tasks (Kawahara et al., 1997). Desktop factories can be used to fabricate tiny products such as micro-motors and micro-actuators; moreover, they can function in small places (e.g., trains, ships), in extreme environments (e.g., manufacturing in the space), in shops or on-site. Small robots can be used for collecting spilled oil, carrying out underground operations, or constructing/dismantling infrastructure (Kawahara et al., 1997). Miniaturized factories exhibit great mobility and flexibility (Zhakypov et al., 2017), can be adapted to the size of the component being manufactured, saving energy and manufacturing space (Kawahara et al., 1997), and can be optimal for small to medium production runs (Breguet, Schmitt, & Clavel, 2000). The concept of 'square-foot manufacturing' shares several elements with the desktop manufacturing configuration; however, the former tends to be smaller and more flexible (Wulfsberg, Redlich, & Kohrs, 2010).

In the domain of decentralized production, Wells and Orsato (2005) define MFs as production units that combine the manufacturing and retailing functions in one site, resulting in multiple small-scale facilities serving local or regional markets. For the authors, these MFs have the potential to make some industries, such as car manufacturing, more ecologically and economically sustainable: they can serve a more diverse demand, they can produce where the customers are, and they can shrink the supply chain by producing and selling on site. Montes and Olleros (2019, p. 1) updated 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". MFs thus have the potential to bridge the gap between artisanal production and mass production, enhance on-demand fabrication, and lower the risks and costs of innovation (Montes & Olleros, 2019).

2.2. 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 computer-assisted design (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". Firms have to select the right product configuration, from several options, to meet customer requirements timely (Liu, Zhang, & Guo, 2018). 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, Alstyne, and Choudary (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 shall focus here on virtual platforms in the manufacturing domain (i.e., OMP).

2.3. Existing Work

2.3.1. 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). 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 (Ware et al., 2018), pharmaceutical (Okwuosa et al., 2018), chemical (Cao et al., 2017), electronic (Qin, Cai, Dong, & Lee, 2017) and spare-part industries (Ghadge, Karantoni, Chaudhuri, & Srinivasan, 2018; Muir & Haddud, 2018). A second branch of literature – software-driven techniques or approaches to on-demand manufacturing – deals mostly with optimization algorithms (L. Zhou, Zhang, Zhao, Laili, & Xu, 2018) and cloud-based applications (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, Anderson (2011), describes the key factors that allow the 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 (2016) 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 intent 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.

2.3.2. Platforms: Existing Literature

The research on online platforms comprises studies on 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) and secure (Fraile, Tagawa, Poler, & Ortiz, 2018), how to regulate (Thelen, 2018) and enforce law on global, boundaryless platforms (Leshinsky & Schatz, 2018), how to protect the privacy of platform users and the data generated (Evans, 2019), and how to deal with surveillance issues (Schneider, 2018). The second domain—competition law and property—focuses on antitrust law and policy (Katz, 2019), anticompetitive conduct (Bostoen, 2018), platform merges/acquisitions (M. Zhou, Leenders, & MeiCong, 2018) and intellectual property (Niculescu, Wu, & Xu, 2018). The third domain—labor and employment implications—emphasizes the impact of platforms on work conditions (Meilhan, 2019), job creation (De Groen, Kilhoffer, Lenaerts, & Salez, 2017), employment relationships (Fricke, 2019), and social security (Schor, 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 (Münzel, Boon, Frenken, & Vaskelainen, 2018; Rachinger, Rauter, Müller, Vorraber, & Schirgi, 2019; Santos, Murmura, & Bravi, 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.

2.4. Initial Research Assumptions

On the basis of previous readings and before starting our methodical data gathering and analysis, we assumed that there were three kinds of economic agents in the local on-demand fabrication ecosystem. First, innovation-driven microfactories (IDMF), which try to reduce the risks and cost of innovation by enabling gradual scalability in new product launches. Second, customization-driven microfactories (CDMF), which seek instead to democratize product customization on an on-demand basis for local markets. Third, online manufacturing platforms (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 1 for some examples).

Table 1. Local On-demand Fabrication: Initial Assumptions

3. Methodology

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).

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

Our main *units of analysis* are MFs and OMPs. We implemented a four-stage process (Figure 1) to identify and select the most suitable MFs and OMPs, gather information about them and analyze them (Figure 2). 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 1. Methods: A Four-stage Process

We used several sources to reliably identify MFs and OMPs: previous knowledge (23 firms identified); previous scientific literature (16), Google search engine (261), InfoTrac Newsstand (32), references in the websites of other firms (10). From those firms we selected 71 that met the selection criteria.

Figure 2. Data Analysis

3.2.1. Experiential Research

For our purposes, we define experiential research as a research inquiry in the digital domain that consist on simulating or performing transactional activities to validate certain entities' claims (Table 2), in our case MFs and OMPs. In some cases, for example, we ordered the design and manufacture of a product/piece to the firms, which allowed us to better gauge their response times, capabilities and interactions with customers.

Table 2. Experiential Research

3.3. 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. 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, knowledgeable 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.

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; also, we adapted some of the criteria proposed by Aguinis, Ramani, and Alabduljader (2017) to increase transparency.

4. Empirical Findings About Microfactories

The information we gathered (Table 3) 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 3, the horizontal axis corresponds to the openness levels and the vertical axis corresponds to the automation levels.

Table 3. Information Sources

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 3. Automation and Openness in Microfactories

4.1. Automation

We have identified two different automation tiers in the cases explored: automation *in production* and automation *in order processing*. We have measured production automation inversely by the degree of human involvement during a product's design, fabrication and testing. And we have 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 have 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 in 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).

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. 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 the shipping address and the 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 and 49 USD respectively.

High-automation microfactories 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.

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 the 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.

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. 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 additional financial resources.

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 of the Figure 4: weakly automated and open (IDMFs), highly automated and closed (CDMFs), and weakly automated and closed (MSs).

Figure 4. Automation and Openness

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 (IDMFs) 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 low volumes. Since they are highly innovative, most of their efforts concentrate on brainstorming, product ideation, development and prototyping for industrial partners.

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, thanks 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).

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.

4.3.3. Weakly Automated, Closed Microfactories

Machine shops (MSs) are mostly conformed by independent fabricators that provide low production quantities of highly customized products for different industries. Our 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 level of human assistance in both, order intake and production. MSs can fabricate distinct products for a broad range of industries, 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 standards online forms are not enough to capture what customers want. 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. Neither do they use crowdfunding or share information, designs and models freely. 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 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.

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.

Independent MFs are small standalone firms that rely on their own financial resources, technologies and partners. For example, a CDMF that 3D prints parts for medical equipment in Kenya, relies entirely on their founders to raise capital and operate the 3D printers. As reported by one of the founders in the interview, the firm's 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).

4.4. Empirical Findings about Online Manufacturing Platforms

Evidently, online 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 they operate diverse and expensive technology. The data we gathered revealed that besides *multisided online manufacturing platforms* (MOMPs), there is an additional type of platforms that we did not consider in our initial research assumptions, *closed online manufacturing platforms* (COMPs). As explained below, the data also shows that two types of MOMPs, low-end and high end, are quite different from each other (Figure 5). Some firms, such as Shapeways, are multisided in some of their markets but not in others.

Figure 5. Multisided and Closed Manufacturing Platforms

4.4.1. Multisided and Closed Manufacturing Platforms

Multisided online manufacturing platforms are lean operators that regulate, curate and streamline 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 in this category. While independent MSs need MOMPs to thrive, corporate CDMFs (e.g., Adidas' Knit-for-you) and IDMFs (e.g., Haier's FirstBuild) do not

Closed online manufacturing platforms (COMPs), on the other hand, enhance the performance of major manufacturers by connecting, optimizing, virtualizing and scaling their own industrial installations. These platforms usually serve only large corporations and their industrial clients. 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.

4.4.2. Low-end and High-end Multisided Platforms

During the data analysis we identified two types of multisided OMPs: *low-end* and *high-end*. (Table 4). Low-end MOMPs connect all sorts of customers with curated and non-curated providers of manufacturing services. 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”, fabricators need only meet a few basic requirements to post their services on the platform.

Table 4. Low-end and High-end MOMPs

High-end MOMPs, instead, match professional and demanding customers with curated manufacturing services. 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, regarding of the manufacturing technology used.

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

5. Discussion

Our empirical exploration corroborated some of our initial research assumptions, but it also provided new insights and challenged some of our premises. 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 anticipated. 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 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 had thought. Besides multisided platforms (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 machine shops (MSs)*.

Moreover, we identified two different types of MOMPs: low-end and high-end. 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.

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. 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 higher levels of automation at both the platform and the factory level. 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 (e.g., 3D Smile). Other companies have migrated completely from the fabrication sector to the online platform domain, such as the firm On Demand Manufacturing Solutions (ODMS). Several platforms seek to differentiate themselves from others (e.g., 3DHubs) 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 3D Hubs 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 precise, 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 offer 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 each other 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 as regards 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, Gershenfeld, and Cutcher-Gershenfeld (2017), Richard D'Aveni claims that the combination of the scale economies enjoyed by software platforms and the scope economies of increasingly flexible 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 the 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.

6. Conclusion

This paper responds to the need to understand the symbiosis between MFs and online manufacturing platforms. Since this is a broad theme, we have tried to explore, contrast and classify different on-demand manufacturing firms and platforms, and then explore the synergy between them. We have tried to do so via a multiple case study that addresses three questions. 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. This taxonomy suggests that there are three distinct types of MFs: innovation-driven microfactories (IDMFs), customization-driven microfactories (CDMFs) and classic machine shops (MSs). We also found a difference between *corporate* and *independent* MFs.

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. *COMPs* are asset and data centric, and enhance the performance of major manufacturers by connecting, optimizing and scaling their own installations and those of their industrial clients. *MOMPs* 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. MOMPs can be *low-end* – connect all sort of customers – and *high-end* – match 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 and their best practices. As this divergence becomes amplified with time, amateur makers may become increasingly marginalized, as their best tools and practices will struggle to keep up with those of industrial suppliers.

As regards 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 of the likely future of manufacturing. On one side, Richard D'Aveni, 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. Small firms will likely thrive along large ones, but will communitarian initiatives do more than just educate or amuse young (or not so young) makers? 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, MOMPs can give independent MFs the chance to thrive alongside the giants. Thanks 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 niche and experimental new 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.

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)?

6.1. Implications for businesses

The trend towards higher levels of automation for platforms and factories keeps steady. 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, automated quality control and 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 scores of brilliant people to design their products and processes 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. 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.

6.2. 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 microfactories 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 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, 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.

7. Declaration of conflicting interests

The authors have had no conflict of interest regarding this research project.

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9. Tables and Figures

Figure 1. Methods: A Four-stage Process

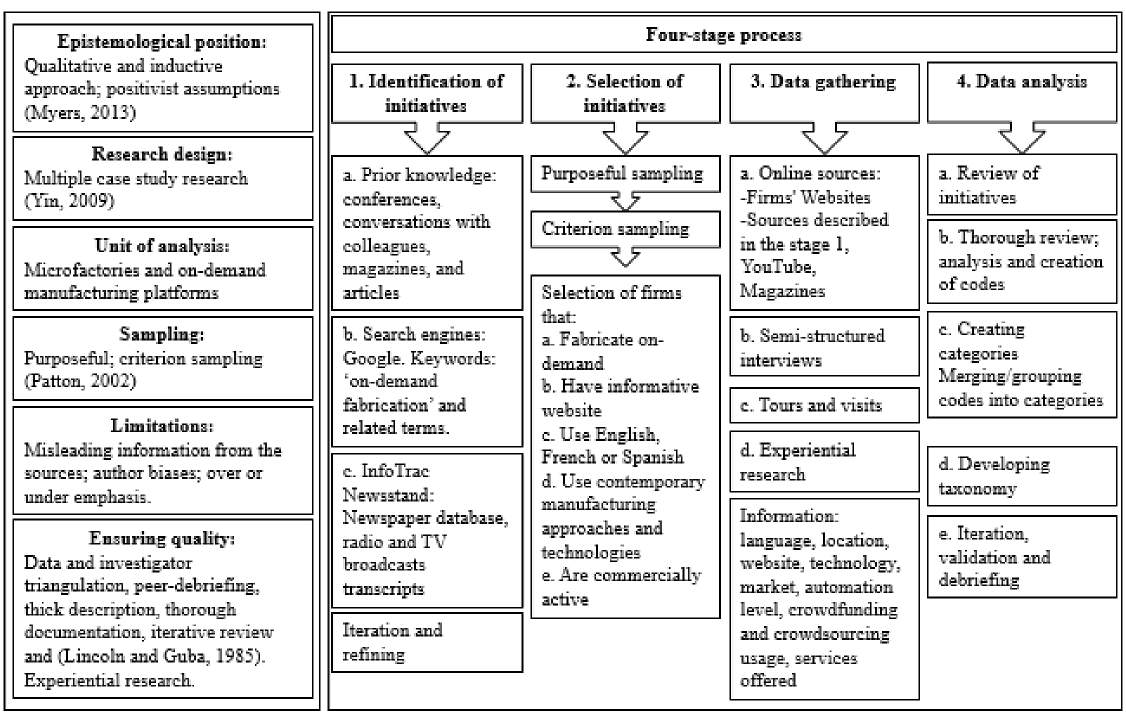

Figure 2. Data Analysis

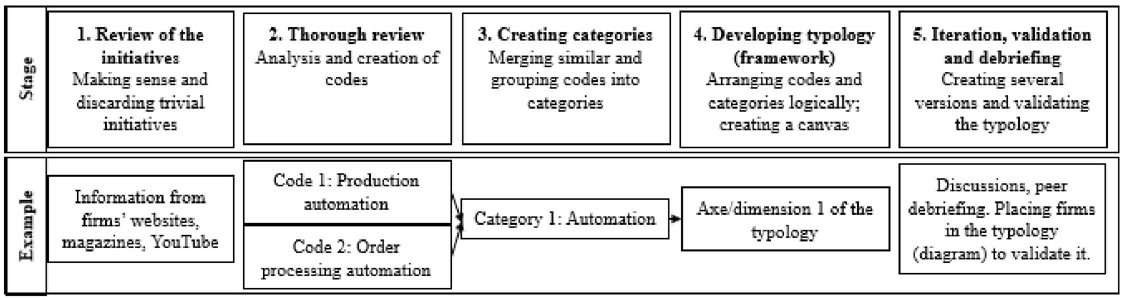

Figure 3. Automation and Openness in Microfactories

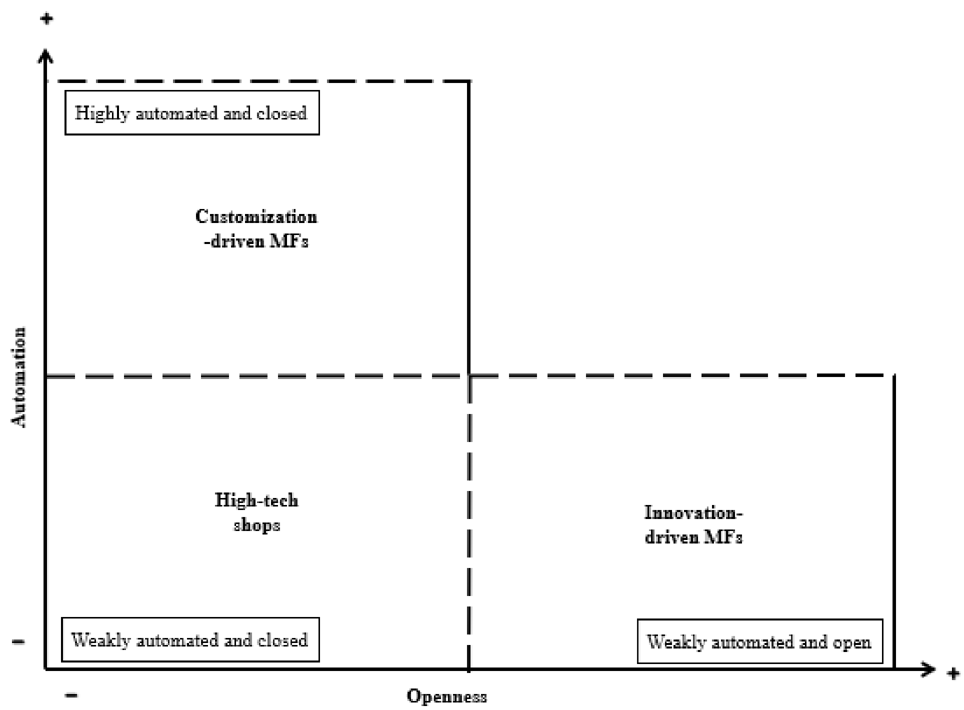

Figure 4. Automation and Openness

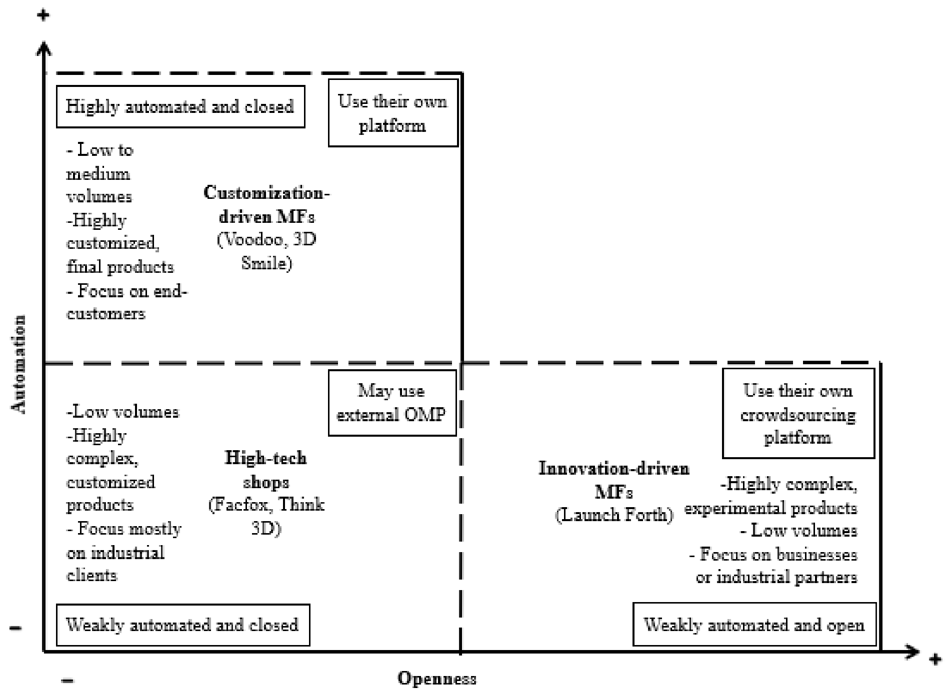

Figure 5. Multisided and Closed Manufacturing Platforms

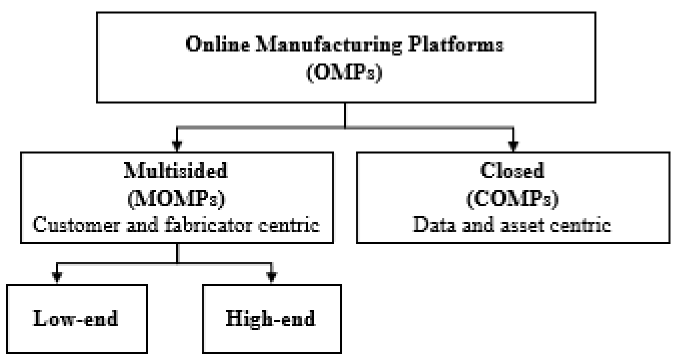

Table 1. Local On-demand Fabrication: Initial Assumptions

		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						

Table 2. 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 c. Most suitable when the objects of study (e.g., firms) are known d. Multipurpose: helps to gather information, validate it and provide descriptions	**Advantages** a. Helps to gather information otherwise hidden or hard to get 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	a. Establish the criteria to identify the object 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	a. Initiate transaction Conduct the experience (e.g., open 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., introduce address, make payment)	a. Provide feedback (e.g., complete firms satisfaction survey) b. Answer e-mails and notifications from the firm
		4. Reporting and comparing		
		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		

Table 3. 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.	

Table 4. 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