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From Smiling to Smirking? 3D Printing, Upgrading and the Restructuring of Global Value Chains

Abstract: 3D printing (3DP) has been heralded as a revolutionary technology that can alter the way production is organized across time and space – with important redistributive effects on geography and size of production activities. In this article, we examine the impacts a widespread adoption of 3DP could have on restructuring, upgrading and the distribution of value added along manufacturing global value chains (GVC) – with brief examples from the aerospace and automotive industries. We highlight two possible scenarios for GVCs: a *complementarity* scenario of 3DP and traditional manufacturing overlapping – which would reproduce power relations in GVCs and the current distribution of value added in a 'smiling curve'; and a *substitution* scenario of 3DP partly or fully superseding traditional manufacturing, which would have more transformational effects – in terms of 'rebundling' of activities, regionalization or localization of GVCs, and a flattening of the smiling curve into a 'smirk'.

Keywords: GLOBAL VALUE CHAINS, 3D PRINTING, MANUFACTURING, RESTRUCTURING, UPGRADING, VALUE ADDITION, SMILING CURVE

Technological advances have been crucial in changing the way in which production is organized across time and space. The steam engine, broadly applied throughout the 19th century, made transportation and manufacturing economic in ways that allowed the spatial separation of production from consumption (Baldwin 2011; 2013). Information and communication technology (ICT) in the second half of the 20th century facilitated the global outsourcing and offshoring of manufacturing activities (Dicken 2015), and the organization of economic activity in Global Value Chains (GVCs) that are dispersed globally but centrally governed by 'lead firms' (see, among many others, Gereffi 1994; Gereffi et al 2005; Bair 2009; Cattaneo et al 2010; Ponte and Sturgeon 2014). The advent of the Internet has facilitated further restructuring, with outsourcing dramatically expanding also in services (Low 2013). The digitization of value chains and the growth of automated manufacturing technologies, such as 3D printing (3DP; also known as additive manufacturing), are currently fueling new restructuring dynamics (Baldwin 2016).

In this article, we examine what impacts a possible widespread adoption of 3DP in manufacturing would have on restructuring, upgrading trajectories and the distribution of value added in manufacturing GVCs, with brief examples from the aerospace and automobile industries. Would 3DP entrench existing structures and power relations in GVCs, or would it have a transformational effect? What kinds of upgrading trajectories would it facilitate or hinder? Would it improve value addition possibilities in production activities – for whom and where?

To start addressing these questions, we first briefly introduce the main features and theoretical debates of GVC analysis. Second, we provide key background information on 3DP and examine some of its main providers and their organizational features. Third, we take a broad-stroke GVC approach to highlight not only the organizational transformations of GVCs that are adopting 3DP, but also possible changes in their power dynamics and in the distribution of value added among different GVC functions. Fourth, by weaving in (necessarily) brief examples from two early-adopter GVCs (aerospace and automotive), we provide nuance to the diversity (but also possible overlap) of possible trajectories of GVC restructuring and upgrading arising from 3DP adoption. Fifth, we examine the potential changes in the relative importance of value addition in different groups of activities (pre-production, production, and post-production) along adopting GVCs, and thus provide preliminary indications on whether the current 'smiling curve' of distribution is likely to change as a result of 3DP adoption – perhaps turning into a flatter 'smirk' that would imply a more equal distribution of value added along GVC functions.[1]

Global value chains: Polarity, upgrading and the 'smiling curve' of value added

In this article, through the lenses of 3DP, we seek to partially answer calls for a more technology-oriented entry point to the analysis of GVC restructuring and upgrading (Morrison et al 2008; Pietrobelli and Rabellotti 2011; Jurowetzki et al 2015). The Global Value Chain (GVC) approach, which has been developing since the mid-1990s, focuses on the role of global players (or 'lead firms') in shaping structures and upgrading trajectories in value chains, and is primarily used to understand the nature and the content of inter-firm linkages that span international borders (Gereffi 1994; Gereffi et al 2005; Gibbon et al 2008; Bair 2009; Mahutga 2012; Ponte and Sturgeon 2014; Gereffi 2014). It is based on the recognition of a progressive disintegration of production, and the general passage from a model of vertically integrated firms to complex forms of coordination between independent actors that are geographically dispersed but functionally integrated (Dicken 2015).

A first key characteristic of this literature is an interest in how GVCs are structured and how relationships among firms are developed in the effort of governing a chain. This led various scholars to examine how authority and power relationships 'determine how financial material and human resources are allocated and flow within a chain' (Gereffi 1994: 97). The GVC literature has underscored the role played by particularly powerful groups of companies, especially those that exert 'buyer power' by placing large orders in their supply chains (Gibbon et al 2008), and how they shape a specific functional division of labour in value chains, with a specific geography (Neilson and Pritchard 2009). Because some activities have higher entry barriers and are more profitable than others, this division of labour influences the allocation of resources and distribution of gains among chain actors (Gereffi 1994; Gibbon and Ponte 2005; Kaplinsky 2005; Gereffi 2014; Ponte and Sturgeon 2014).

In this article, due to space limitations, we mainly reflect upon one aspect of GVC governance – its polarity. Much of the existing GVC literature has focused on 'unipolar' value chains — be they buyer-driven or producer-driven (Gereffi, 1994) – where 'lead firms' placed in one specific functional position play a dominant role in governing, and on identifying what kinds of coordination mechanisms these lead firms enter with their immediate suppliers (Gereffi et al. 2005). Some scholars have also explored GVCs characterized as 'bipolar', where two sets of actors in different functional positions both drive the chain, albeit in different ways (Fold 2002). Others suggest paying attention to broader dynamics of 'contested governance' (Bair and Palpacuer 2015), disarticulation processes (Bair and Werner 2011; Bair et al. 2013), and to the increasing role of actors external to GVCs, such as NGOs and social movements, in GVC governance (Palpacuer 2008; Nickow 2015). Ponte and Sturgeon (2014) frame these observations by highlighting that chains can exhibit 'multipolar' governance, which is different from 'market' as these chains are strongly shaped by the explicit strategic actions of numerous powerful actors – both inside and outside the chain.

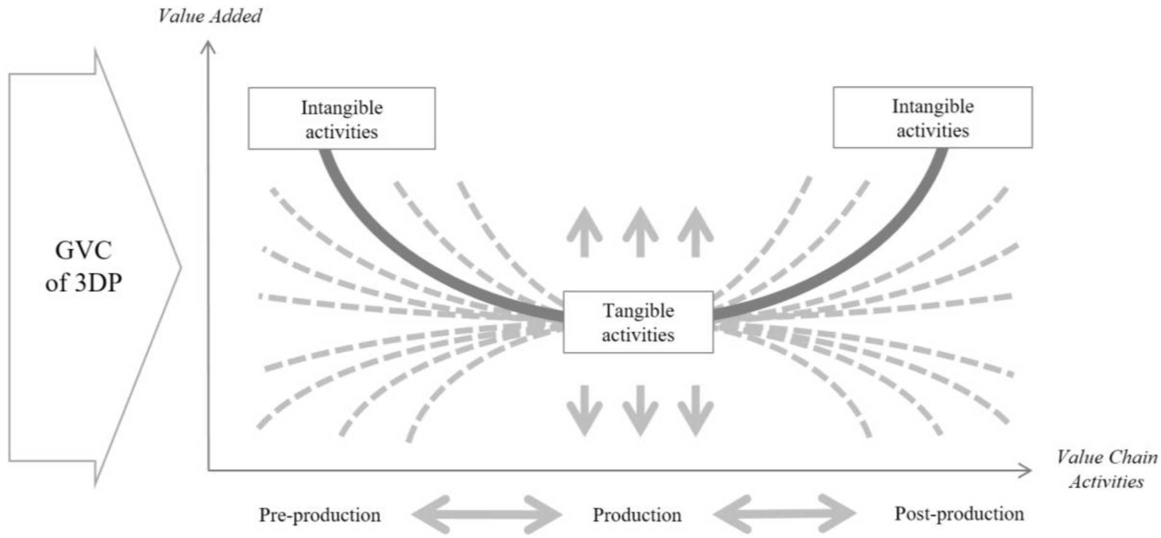
Manufacturing GVCs that adopt 3DP may experience a radical impact on the polarity of governance, for example by moving from 'unipolar' to 'bipolar' or 'multipolar'. This may happen not only because of the role played by 3DP technology providers, but also because of a possible reconfiguration of what it means to be a 'buyer' or a 'supplier' in GVCs that may become more local, less dependent on large scale production, or where the functional distance between production and consumption becomes shorter. These processes may also lead to a disarticulation from global circuits of production, and a re-articulation in regional or local ones (Bair and Werner 2011), leading to a more segmented, complex and multi-faceted picture of governance in GVCs. Alternatively, by incorporating a new technology like 3DP successfully in their operations, lead firms may be able to further consolidate their position and thus strengthen unipolarity (Gereffi 2001; Ponte and Sturgeon 2014).

A second key dimension in GVC analysis is upgrading, a term that has been used to highlight paths for value chain actors to 'move up the value chain' for economic gain. The upgrading process in GVCs is examined through the lenses of how knowledge and information flow from lead firms to their suppliers (or buyers) (Gereffi 1999), with a particular interest in the consequences for entry barriers and distribution of gains (Bair and Gereffi 2003). Upgrading is traditionally analysed through four categories (Humphrey and Schmitz 2002): (1) *product upgrading*: moving into more sophisticated products with increased unit value; (2) *process upgrading*: achieving a more efficient transformation of inputs into outputs through the reorganization of productive activities; (3) *functional upgrading*: acquiring new functions (or abandoning old ones) that increase the skill content of activities; and (4) *inter-chain upgrading*: applying competences acquired in one function of a chain and using them in a different sector/chain.

GVC scholars initially focused on a 'high road' to upgrading, eventually leading to performing functions in a value chain that have more skill and knowledge content (functional upgrading) (Gereffi 1999). But the more recent literature has highlighted a more complex set of upgrading (and downgrading) trajectories (see, among many others, Tokatli 2007; Ponte and Ewert 2009; Cattaneo et al 2010; Ponte et al 2014), while other scholars are re-framing the upgrading discussion in relation to the charting of ‘value capture trajectories’ (Coe and Yeung 2015) and by linking value capture possibilities to strategic management decisions of suppliers and their technological innovation approaches (Sako and Zylberberg 2016) . In this article, we will apply the simpler typology of product, process, functional and inter-chain upgrading when assessing the impact of 3DP on GVC upgrading trajectories in manufacturing.

A third key area of interest in GVC analysis is the distribution of value added among different functions, different geographic locations, and actors of different sizes. Our focus in this article is on functional redistribution, although we provide some preliminary observation on the other two aspects as well. The notion that certain activities in GVCs add more value to the end product than others has affected the way powerful lead firms organize different kinds of activities (pre-production, production and post-production). The idea of a ‘smiling curve’ of value added was first advanced in 1992, when Stan Shih, CEO of the IT company Acer, started steering it away from manufacturing, to focus on developing new service products and strengthening the Acer brand. He called this construct ‘the smiling curve’ (see Figure 1) because ‘the high added-values are located on both ends, the up- and down-streams of an industrial segmental chain . . . The middle stream industrial segment, in the middle of a smiling curve, for assembly works, had become the lowest added-value portion’ (Shih n.d.). This has now become a common observation in the literature (see Ali-Yrkkö et al 2011; Shin et al 2012; Baldwin 2013; Low 2013 – among others).

Figure 1: Conceptual illustration of potential impact of 3DP on GVC restructuring



Source: Authors' own illustration, drawing from the original concept of the 'smiling curve' by Stan Shih, founder of Acer (Shih n.d.).

From a GVC perspective, the 'smiling curve' entails the ability for lead firms to unbundle and outsource low value adding activities, but also the ability to generate technological breakthroughs or to access them. In our article, we examine whether the 'smiling curve' is likely to change in GVCs where the adoption of 3DP is technically feasible, and whether we are likely to see more numerous or fewer functions along GVCs. We do so by discussing the position of the curve (see vertical arrows in Figure 1), its shape (see different curves), and the number of functions included in each bundle of activities (pre-production, production and post-production; see horizontal arrows). Before we do that, in the next section we provide an essential background on 3DP as a technology, and on how the 3DP industry is evolving.

3D printing: Background and evolution

3D printing, also referred to as additive manufacturing, is the process by which material is deposited, layer upon layer, to create a three-dimensional object. Through different technologies (such as powder bed fusion or sheet lamination), 3DP can be applied to a wide range of materials – such as plastics, metals, ceramics, and glass. Key characteristics differentiating 3DP from traditional manufacturing technologies include its additive nature (in contrast to subtractive), and the digital file (called STL) that specifies the product in question, automates the printing process and makes complex products possible to manufacture.

The first version of 3DP was developed under a research project at the University of Texas in the late 1980s. 3DP remained a technology mainly used by and for engineers until the mid-2000s (Lipson and Kurman 2013). Around this time, computing was powerful enough to elevate the printing process to a satisfactory level in terms of speed and quality. This, along with the expiration of key patents, drove prices down and allowed 3DP to enter the market of early enthusiasts for home use, and of designers in most R&D departments for prototyping purposes. Increased internet adoption also leveraged cross-sector learning and facilitated open source innovation in both product design and 3DP software and hardware. C2C platforms like Shapeways were created to educate users of 3DP and to bring its product to the broader market. 3DP took off decisively when it became ready for metal industrial applications and for printing final end parts – a market that is growing at a 60% compounded average growth rate (McKinsey 2014).

According to technology research advisory firm Gartner, the boom in 3DP has only just begun. Gartner estimates that worldwide shipments of 3D printers in 2015 was close to 250,000 units, and is expected to double between 2016 and 2019 to reach a value of USD 5.6 billion (Gartner 2015). The demand for 3DP is not only driven by manufacturers, but also by private consumers, start-ups and learning institutes. Popular media has often coupled 3DP with the word 'revolution', be it 'industrial revolution' (The Economist 2012) 'manufacturing revolution' (ATKearney 2015), or part of a putative 'fourth industrial revolution' (Schwab 2016). But research institutes still struggle to accurately measure the market for 3DP. JP Morgan forecasts a growth to USD 7 billion by 2020, whereas Morgan Stanley's estimate is USD 22 billion (Columbus 2015). In terms of impact on other industries globally, McKinsey (2014) claims it is likely to exceed USD 550 billion by 2025.

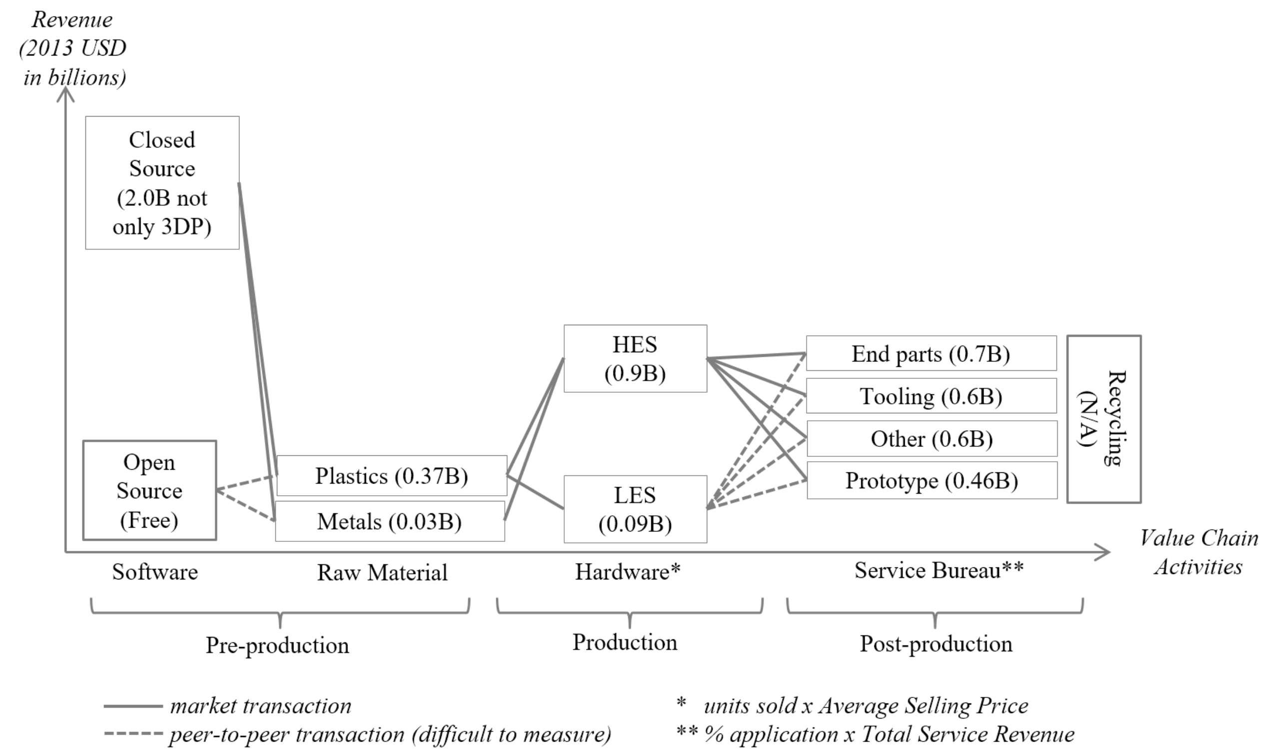
The contemporary growth of 3DP is not only explained by technological advances, but also by two other paradigm shifts in manufacturing – related to business organization and industrial policy. In relation to business organization, the spread of 3DP can be understood in the background of an increased focus on services (Gereffi 2001; World Bank 2012; Low 2013; Sturgeon 2013). 'Servitization' (Vandermerwe and Rada 1988: 314), the rise of 'manuservices' (Bryson and Daniels 2010: 88) and 'servicification' (Low 2013: 2) are some of the concepts used to describe how services have become 'intimately intertwined with manufacturing in all phases, from design and innovation to recycling and waste management' (Gress and Kalafsky 2015: 45). 3DP, along with robotics, big data analytics and the Internet of Things reflect a larger trend of digitization of manufacturing processes aimed at moving closer to demand through agile, data-based manufacturing (Gress and Kalafsky 2015). Furthermore, data is increasingly shared along and between chains through platforms that enable cross business collaboration (Gereffi 2001). Open source platforms have played a key role in developing this technology, in facilitating its widespread adoption in the 'maker' and 'do-it-yourself' 3DP communities, and in fueling innovation to lead firms in manufacturing (Berman 2012; de Jong and de Bruijn 2013; Lipson and Kurman 2013).

In relation to industrial policy, the growth of 3DP has been supported – discursively and financially –by the public sector, along with other technologies (Mazzucato 2013). The EU claims that the increasing adoption of 3DP will usher the 'Factories of the Future', and has set aside €1.15 billion, between 2014 and 2020, to develop high-tech manufacturing processes, including 3DP (European Commission 2013). Germany goes further to frame 3DP into a new manufacturing model, called 'Industrie 4.0' (Zaske 2015). The US earmarked USD 2.4 billion in 2016 alone to support 'advanced manufacturing technologies', such as 3DP, aimed at reshoring manufacturing. President Obama referred to 3DP as a tool for 'making America a magnet for new jobs and manufacturing' (Koizumi 2015). Public sectors in South Korea, China and South Africa are also taking similar steps to redefine manufacturing as a high value added activity through 3DP.

Figure 2 depicts three groups of functions that characterize the provision of 3DP technology: pre-production (software required to design a 3D-printable part, raw materials), production (hardware with which to print), and post-production (the service bureau that actually prints, unless this is done in-house). In parentheses are estimations of the revenues in each function, which determine the approximate vertical position along the Y-axis. In relation to 3DP hardware, we follow an established distinction between higher-end systems (HES) with a market price above

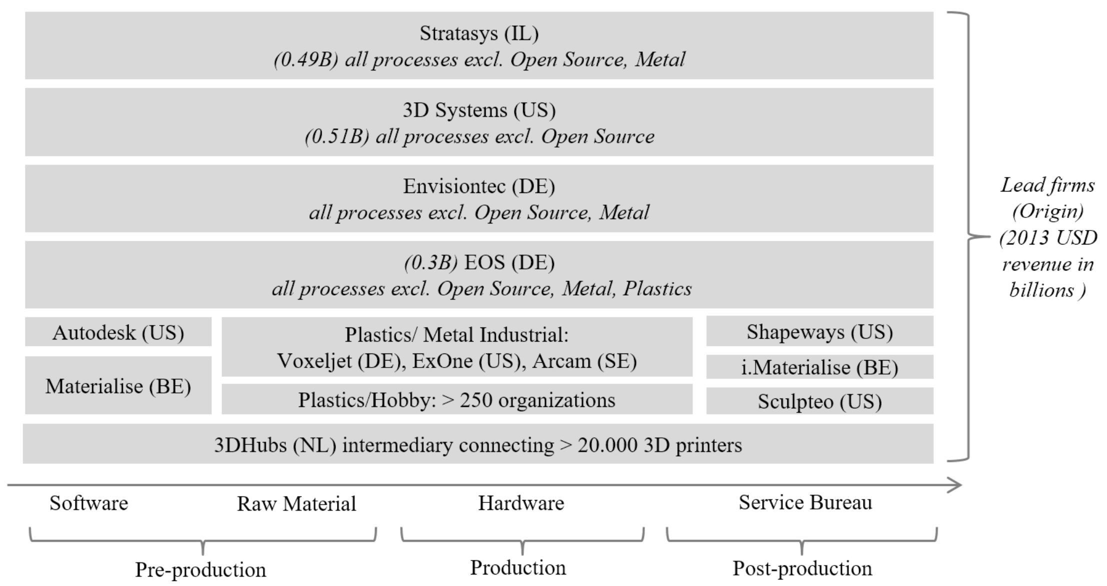
USD 5,000, and lower-end systems (LES) with a market price below that level (Wohlers 2014).

Figure 2: Revenues by bundle of activities in the 3D printing industry



Source: Authors' own, on the basis of categorizations and statistics from Wohlers (2014: 20, 99-129)

Figure 3: Main actors in the 3DP industry



Note: revenue figures in USD bn, 2013
Source: Authors' own, on the basis of categorizations and statistics from Wohlers (2014: 20, 99-129)

Figure 3 indicates the most important firms that operate in each 3DP function, together with estimates of their revenues when available. Noticeable is that many of these firms are vertically integrated, and all are headquartered in the Global North – where they have most of their subsidiaries as well. Among these firms, we find the oldest companies in the field, which have been operating since the late 1980s (3D Systems, Stratasys and EOS). These were founded on the basis of 3DP technologies that were developed, patented and are still chiefly manufactured in-house. Vertical integration suggests that they are competing to become the preferred supplier of dominant designs, underlying technology and raw materials. Most of the HES hardware in fact requires customers to also purchase proprietary design software and raw materials provided by the hardware supplier (Berman 2012).

Vertical integration is not uncommon in industries applying relatively new technologies. However, in time they tend to segment. This seems to be starting to happen in 3DP as well, with the emergence of other companies that focus exclusively on pre- and post-production activities – such as software development, services and consulting for the application of 3DP, and design and certification of 3D printed parts. In the LES segment, we are also observing the emergence of peer-to-peer platforms through which to access 3DP (such as 3DHubs), and of service bureaus that provide certified, local, on-demand 3DP for small batch production or even single piece production. Some degree of regionalization and re-industrialization seems also to be taking place – driven by advanced economies in the Global North with a strong history in manufacturing (see also Gress and Kalafsky 2015). This applies to both supply and demand of 3DP technology and services. Most 3DP production is still kept in-house in the country of origin of the suppliers. As for consumption, 40% of 3DP systems in 2012 were installed in North America, 30% in Europe, 26% in Asia/Pacific and only 4% in other locations (Wohlers 2014).

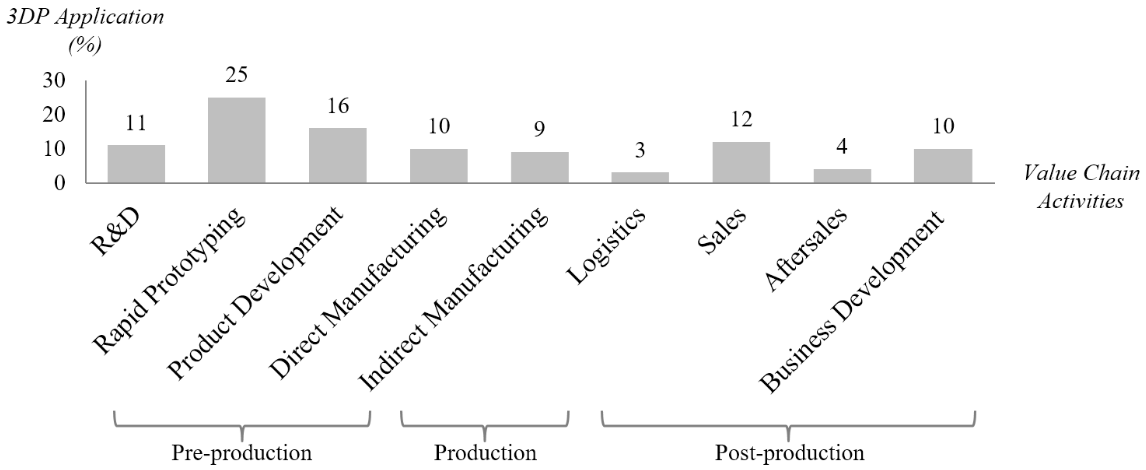
In the next section, we examine the dynamics of 3DP adoption in early-mover GVCs, with specific examples from the aerospace and automotive industries, and how these are shaping upgrading trajectories and possibilities. In a later section, we will examine how 3DP adoption may be (re)shaping the ‘smiling curve’ of value added in manufacturing more generally.

3DP adoption and upgrading trajectories in manufacturing GVCs

The emerging literature on 3DP has examined the development of this technology (Lipson and Kurman 2013), the lessons it yields for innovation processes (de Jong 2015) and its actual and potential impacts on industry structures and geographic location of production processes (Berman 2012; Khajavi et al 2013; Garrett 2014; D’Aveni 2015; Gress and Kalafsky 2015; Kietzmann et al 2015; Laplume et al 2016). Much of this literature highlights the potentially revolutionary impact 3DP has on manufacturing, with personal and peer-to-peer production replacing factory-based operations, and with production re-localizing closer to consumption. Some contributions (e.g. Laplume et al 2016) suggest that the impact of 3DP is likely to be different in different industries – spreading especially in those where materials for fabrication are technically useable for additive manufacturing, and where economies of scale are low, customization needs high, and degrees of automation low.

The literature suggests that in these industries we are likely to see shorter value chains, with decreasing production and trade of intermediary parts, and geographically more dispersed industry structures – thus the likely emergence of denser networks of local producers that are co-located with final users (Laplume et al: 11). In this section, we further contribute to these debates by examining the current applications of 3DP in different groups of activities (pre-production, production, and post-production) in early-adopter manufacturing GVCs, and what they entail in terms of upgrading trajectories.

Figure 4: 3DP application in different manufacturing functions



Source: Authors' adaptation from Gartner (2014). The original question asked in Gartner was 'Where do you apply 3DP?'

Rates and modes of adoption of 3DP vary widely across different GVCs, with selected industries in the lead – such as aerospace, medical, dental, defense, automotive and education. They also vary along different groups of functions in GVCs, with adoption more common in pre-production activities such as prototyping and product development (see Figure 4). To make the analysis as concrete as possible, we draw brief examples from two early-adopter GVCs: aerospace and automotive. Given the space limitations and our focus on 3DP adoption, we do not carry out proper GVC analyses of these two industries, which are available elsewhere (see, among others, Humphrey 2000; 2003; Sturgeon et al. 2008; Van Biesebroeck et al. 2010; Özatağan 2011 for automotive; Bamber and Gereffi, 2013; Sturgeon et al. 2013 for aerospace) – but focus on the specific entry points where 3DP can have an impact on their structures and upgrading trajectories. However, a few features need to be kept in mind. In the automotive GVC, automakers have significantly outsourced the production of parts and modules to specialized suppliers in the past few decades, and these suppliers have also played an increasing role in the design of components and systems (Humphrey 2000; 2003; Özatağan 2011). Yet, automakers have kept a critical role in governing the GVC and in shaping its locational patterns – due to their large buying power (Sturgeon et al. 2008; Van Biesebroeck and Sturgeon 2010). Both automakers and component suppliers have adopted 3DP mainly to decrease the cost of some specialized equipment (molds, jigs and fixtures) and to shorten model design time in pre-production – rather than using it for mass production. In the aerospace

GVC, the shifting of production functions from traditional aerospace strongholds in the US and in Europe to locations in emerging economies has been more recent (Bamber and Gereffi 2013; Sturgeon et al. 2013). This industry has seen a strong trend towards consolidation, with two lead firms dominating the production of long-haul commercial jets (Boeing and Airbus) and two smaller manufacturers producing regional jets (Embraer and Bombardier). The number of first-tier suppliers to these firms has decreased dramatically (Sturgeon et al. 2013). 3DP in this GVC is used for pre- and post-production activities, but also to produce actual end-parts, given the lower volumes needed and the high cost of some materials.

3DP is highly suitable in manufacturing activities where production volumes are small and economies of scale less important. In aerospace, General Electrics (GE) has recently presented its new LEAP Engine, which is equipped with 19 3D-printed fuel nozzles in alloyed metal (Kellner 2015). GE plans to execute its plan to 3D print in-house 30% of its product portfolio by 2020. In industries where production is more reliant on economies of scale, such as automotive, early adopters have used 3DP mostly for pre-production stages such as prototyping or casting molds. But even in automotive, 3DP is making small inroads in production as well: in 2014, US-based Local Motors showcased its 'Strati', the world's first 3D printed electric car that took 44 hours to print, and consisted of a mere 50 individual parts (a traditional vehicle has approximately 30,000 individual parts) (Gastelu 2014). In the next sub-sections, we provide a detailed picture of 3DP adoption in pre-production, production and post-production activities – with specific details related to the aerospace and automotive GVCs – and what kind of upgrading trajectories 3DP may shape (see summary in Table 1).

Table 1: 3DP and upgrading trajectories in the aerospace and automotive GVCs

	Pre-production	*Production*	*Post-production*
3DP in Aerospace	*Process Upgrading:* .) Product development cycles shortened *Product upgrading:* .) Freedom of design and new materials .) Product life cycles extended	*Process Upgrading:* .) Tooling costs reduced .) Assembly reduced .) Economies of scope reduces cost for low batch production .) Material waste reduced .) Digitalization reduces errors	*Process Upgrading:* .) Lead times to market reduced .) Supply chain costs in packaging, warehousing, logistics and transportation reduced *Product Upgrading:* .) Mass customization
3DP in Automotive	*Process Upgrading:* .) Product development cycles shortened	*Process Upgrading:* .) Tooling costs reduced	*Process Upgrading:* .) Lead times to market reduced

Opportunities for *Functional Upgrading* and *Inter-Chain Upgrading* present in both GVCs across each group of activity

Source: Authors

3D printing in pre-production activities

R&D

The additive layering process of 3DP enables the standardized production of complex structures and designs, and the creation of new products (Lipson and Kurman 2013). What we see emerging are complex lattice structures and inner hollows, in materials never used before – e.g. carbon infused plastics that are stronger than metal, and nano, bio and active materials that respond to their external environment (Lipson and Kurman 2013). From this perspective, 3DP adoption in R&D clearly relates to *product upgrading* trajectories, i.e. 'moving into more sophisticated product lines' (Humphrey and Schmitz 2002: 1020).

The challenge for established companies is learning how to re-design parts for 3DP, rather than to replicate traditional parts. Thus, succeeding with 3DP in R&D is about developing new standards suitable for the new structures and materials that are 3D-printed (Lipson and Kurman 2013). In the automotive GVC, numerous partnerships exist to co-develop 3DP concepts. For example, Peugeot and Materialise co-created a concept for a unique sound-trapping texture for an electric car. In the aerospace GVC, GE Aviation maintains close partnerships with the leading suppliers of 3DP, and holds yearly 'hackathons' – competitions where they invite designers globally to partake in the re-engineering of existing GE products with 3DP. This means that in addition to product upgrading, 3DP can also provide opportunities for *inter-chain upgrading*, where actors can gain access to new GVCs that were not previously accessible to them.

Rapid Prototyping

There are three main reasons why we see a higher adoption rate of 3DP in 'rapid prototyping' (RP) than in other activities along GVCs (see Figure 4). First is cost savings: a 3D printer for the purpose of RP can cost as little as a couple of hundred USD. In contrast, a traditional 'rapid prototyping machine can cost as much as 500,000 USD' (Berman 2012: 156). Second is the ease of use of 3DP, due the integrated design software in both HES and LES. For LES, the software is made accessible through open source platforms or design packages such as Google SketchUp and Tinkercad (Lipson and Kurman 2013). The lower price and increased user friendliness of 3DP for RP has facilitated bringing a previously costly process in-house. This cuts design time and shortens the lead-time to market of new products, the third reason why 3DP is valuable for RP (Berman 2012).

As a result of decreased cost and time, both the aerospace and automotive GVCs are using 3DP for RP. An example in aerospace is the Gas Turbine Research Establishment (GTRE Group), which uses 3DP to prototype various gas turbine components – decreasing cost and shortening production time of prototyping dramatically. An example in the automotive GVC is the RP center at General Motors, which has been able to double the amount of models commercially produced since the introduction of 3DP. As Kietzmann et al (2015: 211) observe, 'the speed and convenience of rapid prototyping allows firms, small and large, to be more nimble and to produce different versions of a product overnight, test them, and produce improved versions without delay'. This means that established companies adopting 3DP for RP can achieve both *process upgrading* and *functional upgrading*, sometimes even bringing a previously outsourced process back in-house (Lipson and Kurman 2013). The lower cost of RP may also facilitate *inter-chain upgrading,* where competences in one GVC are used to gain entry in another.

Product Development

The purpose behind 3DP activity in product development relates to both *product* and *process upgrading*. In aerospace, this is well exemplified by the 3D-printed GE fuel nozzle we mentioned earlier, where the strength to weight ratio was increased to extend the product life cycle by five times, also making the part 25 per cent lighter (GE Global Research n.d.). 3DP can thus be used both to improve properties in existing product portfolios and to 'transform inputs into outputs more efficiently' (Humphrey and Schmitz 2002: 1020). The very nature of 3DP (layering) makes it possible to save up to 90% in material waste, in comparison to traditional, subtractive manufacturing technologies (Khajavi et al 2013). Even though a 3DP raw material is currently more expensive than that used for traditional manufacturing, material savings can make 3DP competitive in some applications – and especially in the production of parts with pricey materials, such as titanium, gold and other expensive metals (Berman 2012; Laplume et al 2016). In the automobile GVC, for example, EOS and Warwick University have recently developed an innovative drive shaft for Formula 1 racecars – its carbon fiber and titanium composite is 73% lighter than its steel predecessor (EOS n.d.). The car that Local Motors is developing uses new materials altogether, which can only be 3D-printed, such as carbon fiber blended with thermoplastics.

3DP in production activities

Direct manufacturing

According to Gartner, a technology can be considered mature once it has penetrated 20% of its target industry (Gartner 2014). In direct manufacturing, the penetration of 3DP for volume production of final end parts stood at 11% in 2014 (D'Aveni 2015). Compared to applications in prototyping, 3DP has had more difficulty in spreading to production activities. This is partly explained by the limited range of materials that are suitable for layering, and partly by the still significant acquisition cost of HES used for many applications in industrial manufacturing. At the same time, 3DP does not require economies of scale in order to return positive returns on investment compared to traditional manufacturing (Khajavi et al 2014; D'Aveni 2015). Thus, when suitable, conversion to 3DP can occur really fast – the US hearing aid industry moved to 100% 3DP in less than 500 days, and 'not one company that stuck to traditional manufacturing methods surviv[ed]' (D'Aveni 2015: 43). In aerospace, Airbus has just announced its plans to open a 3DP factory in Germany called the E-Aircraft System House. In partnership with nine actors across aerospace and defense, the 3DP industry and academia, their focus will be on manufacturing light-weight, complex structures for propulsion systems.

Economies of scope are key in creating profitable manufacturing operations with 3DP technology. The cost of a specific investment in manufacturing is significantly reduced by the ability to print highly complex designs in small and diverse batches, at small or no marginal cost per part. In aerospace, for example, full volume production of GE's 3DP fuel nozzle will reduce manufacturing costs by 75 per cent (Kellner 2013). Where the relation between quantity and level of customization is lower, as in the automotive GVC, 3DP has so far been unable to compete with traditional manufacturing technologies such as milling or machining, except in niche applications – good examples are the tens of thousands of parts printed for the Rolls-Royce Phantom collection, or the 3D-printed water pump wheel for racecars. In sum, while there are obvious possibilities for *process upgrading* in manufacturing activities, its achievement is also tied to *functional upgrading* – in particular, the ability to evaluate which products and parts are suitable for 3DP (Appleyard 2015).

Indirect manufacturing

An important opportunity is provided by 3DP in indirect manufacturing activities, where 3DP implies the elimination, or at least a reduction, in the number of stages of production. One of the more obvious is the elimination or reduction of assembly in the production of finished goods that are directly printed out of raw material – what Laplume et al (2016) refer to as the 'technological inseparability' of 3DP. In the event that certain 3D-printed parts need assembly (e.g. for rotating or multi-material parts), 3DP can significantly reduce the process of acquiring components and machines needed for post-production activities (Khajavi et al 2014), and therefore also reduce the need for machine tooling (Lipson and Kurman 2013). Other processes eliminated with 3DP include the use of molds to shape parts and various jigs, fixtures and gauges used to position and organize parts and sub-assemblies throughout the manufacturing process. These are all specialized and costly components that decrease in number with 3DP, and so does their packaging (Lipson and Kurman 2013; Khajavi et al 2014). Finally, some 3D printers can also print spare parts for themselves (Laplume et al 2016). Thus, for products with high asset specificities and/or intensive and specialized labor, 3DP adoption entails *process upgrading*, or even abandoning some processes traditionally needed for production (Appleyard 2015).

In the automotive GVC, sand 3DP is now integrated into manufacturing at BMW, where it is used to produce molds and cores that are later used to cast. In the jigs and fixture department, many tools are now 3D printed in plastics with a FDM printer. This way, BMW uses 3DP as a complement to traditional manufacturing technologies (Stratasys 2013). Another way of doing so is to produce tools for traditional manufacturing equipment. In the aerospace GVC, 3DP is now used at Aurora Flight Sciences to produce specialized tools that cut lead time from months to days or even hours. Tooling is also one of the main applications of the 3D printer currently in orbit – printing ratchet wrenches for NASA (Black 2015).

3DP in post-production activities

Logistics

The vision of decentralized production is that '[d]esigns, not products, move around the world: digital files to be printed anywhere by any printer that can meet the design parameters' (Garrett 2014: 71). For logistics, this vision implies a decrease in transportation, inventory and warehousing costs (Khajavi et al 2014). Among established businesses that have invested in 3DP to achieve *product upgrading* are UPS, DHL and Amazon. UPS is turning several existing hub warehouses at airports into mini-factories, where 3DP is 'used to produce and deliver customized parts to customers as needed, instead of shelving to vast inventories' (D'Aveni 2015: 46). Furthermore, local 3DP can serve as way to bypass import barriers (Laplume et. al. 2016). Among third parties that are providing services around decentralized production using 3DP, a pre-requisite is that information is shared securely to protect the intellectual property of designs – a digital and cultural infrastructure that may explain the lower adoption of 3DP in this area, as revealed in Figure 4. Intellectual property considerations also explain why some 3DP activities are kept in-house –as in the cases of GE and Airbus in aerospace, and BMW in automotive.

For industries such as aerospace, on-demand and decentralized 3DP facilitates *process upgrading* – alleviating the 'supply chain pains' of remote location of operations, highly specialized equipment, or limited ability to keep high stock to mitigate risks of downtime. In the NASA example, twenty additional parts of a ratchet wrench are currently being 3D printed while in orbit. While for NASA, the highest supply chain pain is distance to spare parts, this issue is less important for the automotive industry, since its products are more standardized and therefore also easier to access.

Aftersale and sale services

The major benefits of 3DP in aftersales services are related to the savings that can be achieved by reducing the lead-times of specialized parts (and so the risk of downtime). Benefits also arise from mitigating the risk that parts with a long lifetime become obsolete – by holding digital stock of the blueprint of the product in question. In aerospace, for example, Airbus was recently in need of a plastic safety belt holder, the supplier of which no longer existed. The molds for the parts were lost and rebuilding them would have cost thousands of dollars – a costly investment for only supplying around 100 parts a year. Instead, Airbus redesigned the 30-year old design in two hours and had the part 3D-printed a week later (Airbus 2014). In automotive, with the exception of parts for vintage cars, such as Elvis Presley's BMW 507, such demand is less relevant, as cars have a shorter lifetime, quantities are higher, and standardization more extensive (Hall 2016).

The benefits of aftersales services will typically trickle into sales departments, which need to rethink the pricing models of 3D printed products. For instance, in both aerospace and automotive GVCs, cutting the weight of a product through 3DP can translate into fuel savings for the end customer, stronger parts can reduce the amount of overhauls required during a the product lifecycle, and decentralized production can shorten lead times and reduce the risk of downtime. All three are instances of *product* *upgrading* that manufacturers can price accordingly for their end customers.

Business development

Across all stages of production in which 3DP is applied there are windows of opportunity for business development through *inter-chain upgrading* – entering 'into a new value chain by leveraging the skills acquired in the current chain' (Gereffi 2014: 9). DHL, Amazon and UPS are entering the realm of production, and thus re-thinking their product offering and/or tweaking their existing business models with 3DP. While their core competency is to get products from destination A to destination B, they are now considering whether this needs actual physical transport – or whether they would be better off creating the product directly at destination B.

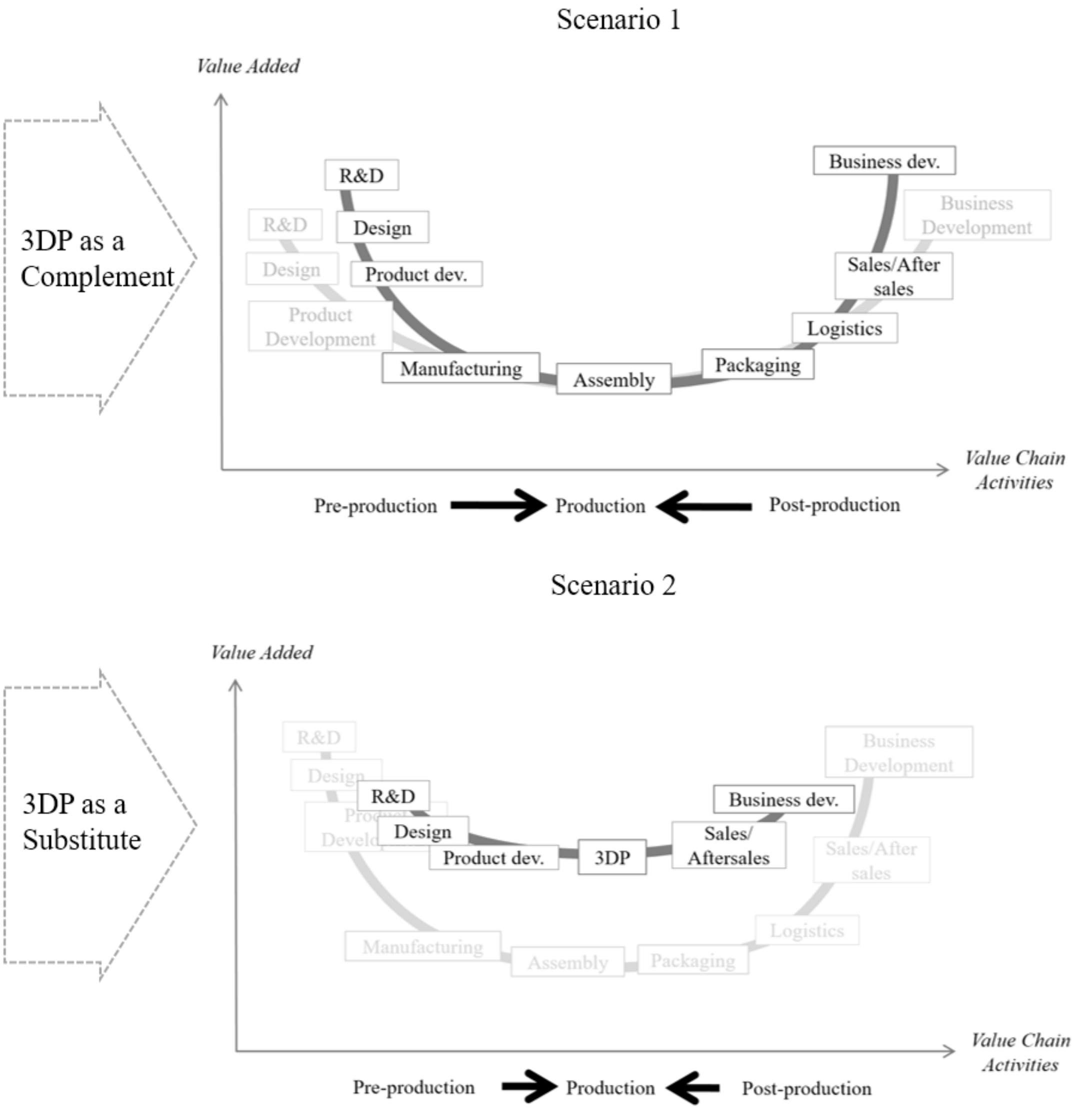
Another common upgrading strategy is pursued by actors that have developed 3DP skills that can be leveraged in other GVCs. In the aerospace GVC, key actors have understood the value of the competencies they developed around 3DP and are now leveraging them in other GVCs. For example, Airbus in 2013 started a consultancy arm called APWorks, to expand their use of aerospace technologies in other industries. APWorks serves as delivery channel for patented technologies and as a means for Airbus to pursue *inter-chain upgrading* (into robotics, mechanical engineering, medicine and even the automotive industry). Also interesting is that APWorks uses the platform 3DHubs to make their 3DP hardware accessible. 3Dhubs started out as a C2C platform for private 3D printers connected in a global platform, accessible for consumers who have an idea or design but no printer (see Figure 5). Today it has over 30,000 printers connected globally, with an average lead-time of two days, making just-in-time production an affordable reality (3Dhubs 2016). Platforms like these enable low cost manufacturing that can significantly decrease barriers of entry in many other industries.

In this section, we examined to what extent and how 3DP is being adopted in different manufacturing GVCs and for what activities. We also highlighted a variety of upgrading trajectories that 3DP adoption is facilitating (see summary in Table 1). It is still early to assess which types of upgrading will be more dominant and with what results, but it is clear that inter-chain upgrading is a dimension of particular salience. In the next section, we explore how 3DP may restructure manufacturing GVCs more generally, and what this would mean for the polarity of governance and the ‘smiling curve’ of value added.

3DP, GVC restructuring and the ‘smiling curve’ of value added: Two scenarios

The increasing adoption of 3DP in manufacturing suggests numerous implications for adopting GVCs – as producers are acquiring new capabilities, new actors are accessing GVCs, and transaction-specific investments are decreasing. In Figure 5, we formulate two scenarios, which are ideal-typical but not meant to be mutually exclusive – as they are likely to continue co-existing. The distinction between the two is useful, though, as each has distinctive implications on GVC restructuring and on how value added is likely to be distributed along GVCs. The first is a *complementarity* scenario, in which 3DP and traditional manufacturing technology overlap. The second is a *substitution* scenario, where traditional manufacturing is superseded (fully or significantly) by 3DP (see Figure 5 and Table 2).

Figure 5: 3DP adoption and the 'smiling curve' of value added – Two scenarios



Source: Authors
Note: darker line denotes possible future scenario; lighter line denotes status quo

Table 2: 3DP adoption and GVC restructuring in manufacturing – two scenarios

Aspect of restructuring	Complementarity scenario	Substitution scenario
Production technology	mainly remaining in traditional manufacturing	moving significantly to 3DP
Number of functions in the GVCs	cost reductions may lead to some reduction (rebundling)	significant reduction (rebundling)
Geographic distribution of functions	not changing significantly	decentralisation and localization; production moving closer to the consumer
Actor-size distribution	not changing significantly; but more small-scale actors could afford 3DP prototyping	large- and small-scale operations co-existing
Influence of 3DP tech providers in adopting GVCs and vice versa	limited	significant
Polarity of governance	strengthening existing situation	pushing towards multipolarity
Value added distribution	becoming more skewed towards pre- and post-production; 'more smiling' curve	becoming more equally distributed along the value chain; from smiling to 'smirking' curve
Upgrading trajectories	mainly process, some functional and inter-chain upgrading	mainly process and inter-chain, but also significant product and functional upgrading

Source: Authors

In the *first scenario*, 3DP is applied for rapid prototyping in pre-production activities, or to manufacture specialized machine tooling for production. 3DP is used to decrease development cycles of products that are subsequently mass-produced using traditional technology and infrastructure. This implies a new level of control and coordination, not primarily driven by product quality or quantity, but by control over time and space to supply customized products in the right location at the lowest possible lead-time.

In this complementarity scenario, 3DP moves 'the source of competitive advantage away from the ability to manufacture in high volumes at low cost and toward other areas of the value chain, such as design or even the ownership of customer networks' (McKinsey 2014). A further entrenching of existing GVC structures takes place as power is strengthened in the hands of actors who have access to information on the needs of the end customer. Value added moves further away from production and into pre- and post-production activities, thus deepening the smiling curve (see Figure 5, top part). The number of functions and their geographic and actor-size distribution do not change dramatically – although cost reductions may facilitate some degree of 'rebundling'. Finally, lead firms in the 3DP industry do not come to play a direct role in the governance of adopting GVCs, thus do not alter their polarity.

In the *second scenario*, production in specific GVCs moves more significantly to 3DP, and away from traditional manufacturing. In this substitution scenario (Figure 5, bottom part) production becomes more decentralized and closer to the end-consumer. 3DP reduces the need for assembly, packaging and transport, and thus decreases the number of functions in GVCs altogether – through a marked process of 'rebundling'. Production becomes even more on-demand than in the first scenario, and the 'smiling curve' of value added flattens to become more like a 'smirk' – with value added being more equally distributed along re-bundled functions. Although in Figure 2 the 'smirk' curve is placed at a higher level of value added overall, this is not necessarily the case. Like in the first scenario, the position on the Y-axis will depend on the ability of value chain actors to access consumer data valuable for mass customization. It will also depend on their ability to make full use of 3DP to design new products and, in a way, formulate new customer needs. Power, in this scenario, is likely to be in the hands of the data analytics for high value added customization, and in creative design for radical product innovation.

In this substitution scenario, the geographic distribution of functions changes more radically than in the complementarity scenario, with production moving closer to consumption markets and with GVCs taking more regional/local configurations. This could involve some degree of 'reshoring' of functions to North America and Europe, given that these two regions are (for the time being) dominating installed capacity and demand for 3DP. Large-scale and small-scale operations are more likely to coexist. We are also more likely to observe a significant role played by 3DP lead firms in adopting GVCs, and/or, conversely, lead firms in adopting GVCs making inroads in the 3DP industry. These dynamics suggest a possible transition to more multipolar governance structures in GVCs – at least in the mid-term.

Conclusion: Smiling or smirking?

In this article, we examined the possible restructuring dynamics, upgrading trajectories and distribution of value added in manufacturing Global Value Chains (GVCs) that are more likely to adopt 3D printing in their operations. We highlighted how the 3DP industry is for the time being characterized by vertical-integration, with dominant technology developers based in the Global North carrying out operations with significant service content and intellectual property control. We also traced the multiple trajectories of upgrading that 3DP can facilitate in different functions along manufacturing GVCs – with brief examples from the aerospace and automotive industries. We showed that a broad range of upgrading trajectories (including significant inter-chain upgrading) are taking place in the aerospace GVC along all groups of activities, while process upgrading is the main form taking place in the automotive GVC, and mostly limited to pre- and post-production activities.

Furthermore, we identified two ideal-typical scenarios of how 3DP may restructure manufacturing GVCs: a complementarity scenario and a substitution scenario. Under the complementarity scenario, we expect that in GVCs where production volumes are higher and economies of scale more important, the impact of 3DP is likely to be limited mostly to pre- and post-production activities. In these GVCs, existing structures and power relations are likely to be reinforced by the adoption of 3DP. Under the substitution scenario, we expect that in GVCs where production volumes are low, economies of scope more important, and where production materials can be processed through layering technology, 3DP could facilitate a significant transformation. This could include a tendency towards more multipolar forms of governance, and expanded roles for 3DP lead firms in adopting GVCs (and possibly vice versa).

One of the main differences between the two scenarios lays in how value is likely to be distributed across GVCs. In the complementarity scenario, labor-intensive and lower value added processes would still be present in production, with 3DP likely to reproduce or even deepen the current ‘smiling curve’ of value addition. In the substitution scenario, the relative weight of value addition would be likely to increase in production activities, with the possible transformation of the smiling curve into a flatter 'smirk' – thus a more equal distribution of value added along the ideal-typical GVC. This scenario could also have significant impacts on the geography of production (with a partial regionalization and re-shoring of production activities) and the size of operations (with smaller and larger producers co-existing).

In this article, we have taken a technology entry-point in assessing the possible restructuring trajectories of manufacturing GVCs. Yet, far more work is needed in view of better integrating innovation systems and GVC approaches in the future (Pietrobelli and Rabellotti 2011; Jurowetzki et al. 2015). More research is also needed to further examine: whether advances in materials science and technology allow an expansion of possible applications of 3DP in manufacturing GVCs where it is currently not feasible or economic; whether 3DP adoption leads to further unbundling or rebundling processes and in which GVCs; whether the social organization of production is likely to move away from the factory and back into the workshop; and whether manufacturing jobs are likely move back to advanced economies to the detriment of emerging economies.

From a geopolitical point of view, a key unresolved question is to what extent a possible redistribution of value added along GVCs would impact different countries – given that lead firms supplying 3DP technology and lead buyers of it are predominantly based in North America and Europe for the time being (see Hicks 2014). While first-movers in the Global North are currently pursuing the technology promise of 3DP, the future role of actors in other regions with limited access to 3DP technology and know-how is still unclear. More research is also needed in establishing whether shifting global end-markets would affect the two scenarios laid out in this article, and what could 3DP adoption mean in terms of the identity of lead firms and key buyers in GVCs, and in terms of the vertical position of the smiling/smirking curve of value added.

Finally, we need to know more about how 3DP is accessed globally from the point of view of both producers and consumers. As internet users increase, especially in the Global South, and digital technologies of the fourth industrial revolution improve in price and performance, it is not unreasonable to expect a paradigm shift in manufacturing. Should the number of 3DP users continue to grow at the current rate, the way in which we define value, transactions, products and buyers could change significantly.

Notes

[1] The empirical material used for this article arises from several years of hands-on professional involvement in the 3DP industry by one of the authors and from a collaborative research project involving the two authors. This combination has provided in-depth and direct knowledge of 3DP, together with a theoretically-inspired and arms' length analytical approach. One of the authors has been directly involved in the 3DP industry for four years, both as a consultant and as a project manager for a major firm interested in adopting 3DP solutions. In that capacity, she has carried out eight workshops with over 200 3DP technology providers and users in several industries (some of these workshops were at the senior management level), was a keynote speaker in another nine conferences on 3DP, and attended several other conferences as a participant. Although these were not carried out with research purposes in mind at that time, the material collected (documents, presentations and notes or recollection of conversations) formed the basis of a subsequent research project carried out in 2015/16 by both authors. This included supplementary secondary data collection and ten semi-structured interviews with key 3DP informants (academics, business leaders, entrepreneurs and policy makers). Additional details are available from the authors.

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