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A Framework for 3d Printing

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Abstract

3D printing technologies and processes offer such a radical range of options for firms that we currently lack a structured way of recording possible impact and recommending actions for managers. The changes arising from 3d printing includes more than just new options for product design, but also shifts in the manufacturing eco-system and choices for restructuring competitive dynamics. We review many existing cases and developed a taxonomy capable of capturing the many areas of impact. The taxonomy draws on Pavitt's identification of industry types, combined with Castellacci's more recent service-manufacturing sectors which includes external sources and more open business models.

Keywords: 3D printing; Industrial Taxonomy, Competitive Dynamics.

Introduction

Despite much recent attention concerning additive manufacturing or 3D printing in the popular press, we are aware from our work with various Danish manufacturing firms that there are more opportunities presented by the technique than just making plastic toys locally to a user produced design. In the technical and engineering management literature, there is an appreciation that aside from novelty, the technology is a way of reducing supply chain time and complexity. However, there are some aspects which have failed to penetrate even the technical literature or the minds of managers exploring its implications. After attending and organizing several workshops with local companies, we are aware of some of the opportunities for the technology and are starting to investigate how best to help firms exploit additive manufacturing and also its potential wider impact. Areas not fully appreciated to date include customization due to very late production and design cycles, allowing innovative design ideas (e.g. previously impossible cooling channels in injection moulds), the abolition of a need to hold inventory (particularly in spare parts), changing import duties (parts are made locally from generic materials and not transported over boarders), even challenging the need for logistics (making items at hubs means there is no need for shipping), etc.

As such, there has been little systematic work to identify and classify the multitude of ways in which the technology can be used as a strategic weapon to give competitive advantage. It is here that we seek to make our contribution in developing a framework to assess the potential disruption caused by the approach and offer firms a means of assessing this technology beyond its obvious application as a production method.

We based our taxonomy on Pavitt's identification of industry types based on innovation and dominance, but extended this with Castellacci's more recent service-manufacturing sectors which includes external sources and more open business models (Castellacci, 2008; Pavitt, 1984). In addition to offering a comprehensive framework for plotting and comparing the impact of 3D printing, we emphasise the role of users in co-creation and personalisation and how this varies according to the level of use of 3D printing at different stages between end products and various types of manufacturing strategies.

Additive Manufacturing Literature

There are a limited number of studies which deal with additive manufacturing in the engineering and management literature. But none take a stance which allows the identification of the size of radical change which the technology seems able to provide. Here we are conscious of work which deals with new business models such as that offered by Sinfield et al (2011) or the similarly seismic change afforded by perspectives of technological alignment and convergence. At present the focus is on the explicit nature of the technology and not on the tacit nature of exploiting the opportunity arising from such radical change.

Bogers et al. (2016) argue that 3D printing is changing, and in some cases radically disrupting, power structures and supply chain dynamics. This forces firms to introduce many changes and enables the startup of new firms. However, understanding these changes is a rather complicated matter (Rayna and Striukova, 2016). Limits to the size of goods produced by 3D printing, difficulties in achieving mass production, issues with materials, and certification standards constrain adoption of this technology in some industries, but not others (United States Government Accountability Office, 2015). While this technology is evolving and has the potential to transform manufacturing ecosystems, a granular understanding of the socioeconomic consequences of 3D printing lags activity (Ford et al., 2016). Empirical investigations of how different industries have transitioned to, or employed, 3D printing technologies are sparse. This paper undertakes a detailed review of the application of 3D printing technologies in different industries to understand the impact of 3D printing on business ecosystems and the implications for firms and customers. As such we adopted an illuminative research strategy in which we sought exemplar organisations within different types of industries in order to understand the changes that 3D printing has brought to their ways of operating.

The advent of 3D printing, has been seen in traditional industries as an example of a disruptive innovation (Christensen 1997; Christensen and Raynor 2003; Rayna and Striukova, 2016), and has been described as an accelerated move towards the digitisation of manufacturing. Its impact has been substantial, leading to radical and even Schumpeterian changes in industries and the manufacturing landscape (Manyika et al., 2013; Petrick and Simpson, 2013; Rayna et al., 2015; Rayna and Striukova, 2016; Schumpeter, 1939). Technological transitions such as this influence existing industries, encourage the development and expansion of new industries, and even overthrow existing industries (Sandström, 2011; Schmidt and Druehl, 2008). Discussions in the literature have shown that this change in business models encompasses many different styles such as disruption, radical and rapid incremental change. As such, many questions remain pertaining to the fundamental impact of 3D printing and also more specifically on individual firms and industries.

In addition, because of the role of digitisation, 3D printing has also been significant in the newer business models and emerging industries. It has been grouped with other disrupted industries such as digital books and music (Berman, 2012). However, there are some differences, mainly to do with the physical nature of the product: "While movies and music are nowadays predominantly transferred over the Internet to be 'manufactured' at home, it is unlikely that all manufacturing will follow this path, with every single object being fabricated at home on a personal 3D printer" (Rayna and Striukova, 2016, pp. 214-215). However, 3D printing can be used to manufacture low volume customised products that are economically attractive (Berman, 2012; Petrick and Simpson, 2013; Petrovic et al., 2011), accelerating a cultural shift towards do-it-yourself inventing and making (Anderson, 2012).

Our literature review of additive manufacturing identified a limited range of materials, but much of it stresses the technological nature of the innovations involved but does not deal with the potential disruption to business models. These studies are largely one dimensional in considering the impact of the technology and nearly always focus on simple types of change to existing practices. We grouped these studies under the following titles: manufacturing method, user involvement, SCM, prototyping, and design opportunity, and review their focus next.

Several studies compare additive manufacturing to traditional **methods of mass production** (or subtractive manufacturing (Kietzmann et al, 2015)) and draw on the local implications to manufacturing, factory design and economic lot sizes (Berman, 2012). An interesting and novel feature of the work of Gebler et al (2014) is that they extend the relatively simple manufacturing impact idea to model the resulting reduction in CO_2 emissions.

Other populist themes, seen in both the mass media and academic literature, focus on the role of **user communities** or devolved design activities. For example, de Jong and de Bruijn (2013) talk of web democratized innovation and how the technology allows a voice for different sets of communities which have so far been uneconomic to serve with traditional methods. Another idea is to examine the opportunities in evolving supply chains presented by what is termed the maker movement (Waller and Fawcett, 2013). Here the focus is on adapting designs as the manufacturing process becomes less entrenched in existing capabilities and supply chains. Hermans develops a framework examining the different roles of professional design tools in the hands of users (2014).

In a similar vein, the technology has generated interest because of the way it changes the prototyping process. **Rapid prototyping** (RP) and frequent design iterations result from lower investment and more localized production. Another design related opportunity which often appeared in the papers we found includes the ability to generate **innovative design** solutions because of the layering approach. Laying down connectors as part of the additive process, printing with a combination of different materials, and generating complex internal structures are all opportunities which are not normally available to designers using traditional methods. These allow designers to try new solutions. For example, LEGO, one of our local companies involved in workshops, has explored the benefits of higher production rates resulting from faster injection mould cooling when die sets with complex hollow structures are printed.

Another design related issue concerns intellectual property. As designs are widely transferred using open formats, they are easily copied unless particular care is taken (Kurfess and Cass, 2014).

Some work focus on the probable influence of additive manufacturing resulting from its shift in the location of production and **SCM**. For example, Waller and Fawcett (2014) explore the way in which supply chain design could be redefined as products become printed at either central hubs or even closer to the point of usage rather than in traditional mass production units. Their framework deals with the impact on transportation, warehousing and forecasting for both raw material and finished inventory when additive manufacturing becomes economical. In the geography literature, Gress and Kalafsky (2015) talk of the "place-based facets of additive manufacturing" as they try and explore the impact on global supply and demand networks which bring into focus the important role of government and also re-plotting the value chain when raw material supply is direct to dispersed printing hubs. Garrett has a similar focus on policy as he predicts additive manufacturing to be a third industrial revolution (Garrett, 2014).

Some work also talks of the impact of additive manufacturing on specific supply networks. A good example is the work concerning the re-design of spare part supply and distribution. The ability of additive manufacturing to locally and quickly produce selected parts from a very wide catalogue makes it ideal for spare parts. This business is highly unpredictable and very complex. One of our workshop firms is very interested in this as it operates a global ship line and the ability to procure spares through hubs located at major ports would not only reduce downtime, cut the need for storage of a plethora of items with unpredictable demand, but also reduce the import duties paid (Kajavi et al, 2014).

Only a few of the studies we read as part of our literature search offered any detail in more than one potential aspect of the impact of additive manufacturing. Kietzmann, Pitt and Berthon (2015) were almost unique in being interested in the potential disruptive nature of the techniques, and so found multiple impacts as they considered both B2B and B2C relationship evolution in a widespread additive manufacturing world. They structure their study in terms of prototyping, inventory, supply chain, and customization, proposing a framework of potential customers based on functionality and newness of the product. Mellor, Hao and Zhang looked at how a firm might develop a technology strategy to deal with the adoption of additive manufacturing. They chose to consider the strategic, technical, organizational, operational and supply chain factors which must be considered, before reporting a single company case study (Mellor et al, 2014).

In this paper, we address these gaps in understanding how 3D printing is specifically changing the rules of the game and competitive dynamics in these different industries, both modern and traditional (Bogers et al., 2016; Jia et al., 2016). Drawing on secondary data sources on the top industrial users of 3D printing we first develop a model which synthesizes and extends Pavitt's and Castellacci's taxonomies of manufacturing sectors (Castellacci, 2008; Pavitt, 1984). From these typologies we develop a new, extended and updated, taxonomy of industry types that facilitates an understanding of how 3D printing has changed the dynamics of competition, product development processes, and sources of competitive advantage in different manufacturing sectors. The extended taxonomy is applied to develop an understanding of the diversity of sectors and map the differences (Archibugi, 2001).

Multi-Dimensional Models

As we show above, while some papers suggest that the introduction of 3D printing will have significant impact on market structures and competitive dynamics (Bogers et al., 2016; Jia et al., 2016), it is not possible to generalize these findings to all industries. Taxonomies of sectoral patterns show that innovation modes, collaborations, knowledge sources, and therefore business models differ according to industry (Archibudgi, 2001). Taxonomies shape what "firms can and cannot do" (Pavitt, 1998, p.441). This is exactly what we need to engender before extracting ideas about 3D printing-based change. Previous taxonomies of industries, however, do not consider some of the important changes 3D printing enables such as customer involvement, relocation of production, reduction in break-even volumes and alternative design solutions. Therefore, a thorough understanding of firms' behaviour based on 3D technology is necessary and demands an updated categorisation of industries and firms. In this paper, we build a combined model based on Pavitt's and Castellacci's taxonomies of manufacturing sectors (Castellacci, 2008; Pavitt, 1984) to evaluate the wider implications of developments in 3D printing more systematically.

Pavitt's taxonomy (Pavitt 1984) of sectoral patterns describes the behaviour of innovating firms, predicts their actions and suggests a framework for policy analysis (Archibugi, 2001). Pavitt's taxonomy presents patterns of innovation in different categories and presents a theory of innovation flow among the different sector types (see Figure 3). The first category, supplier-dominated firms, tends to be small firms found in traditional industries such as textile and furniture. They typically focus on productivity and acquire most of their technology from outside the firm, from science-based firms and scale-intensive firms. The second category, scale-intensive firms, are often large and oligopolistic. They focus on the increase of the scale and speed of production to generate economies of scale. Innovation is mostly undertaken within their production departments and they often receive technology from science-based firms. The third category, is the science-based sectors, which include firms that rely on internal R&D and have universities and research centres as sources of innovation. The last classification, specialised supplier firms, tend to be small firms which rely on batch production. They produce technology to be sold and supply specialised machinery and tools to their scale-intensive and supplier-dominated customers. Technological linkages among different groups of sectors include transactions involving goods, information, and technological diversification (Pavitt, 1984).

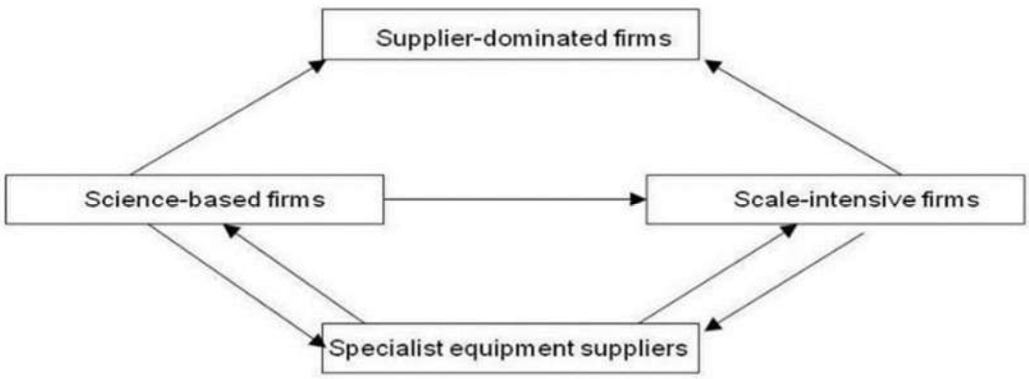

Figure 1 - The main technological linkages among different groups of industrial sectors (Source: Pavitt 1984, p.364)

Pavitt's taxonomy has been used to show that every long wave of capitalist development has generated a new type of innovative firm (Archibugi, 2001). This has not necessarily led to the destruction of pre-existing firms, but simply added new ones. For instance, the Fordist revolution led to the creation of scale-intensive firms. As Archibugi (2001) notes Schumpeterian gales of creative destruction have forced traditional firms to introduce many changes and coexist with new firms characterised by a different technological trajectory. However, Pavitt's taxonomy does not take into account the third industrial revolution of digital technology. The current technological development of the so-called new economy corresponds to a rise in information intensive firms which are based on intensive creation, analysis, use, and visualization of data. ICT has empowered consumers with the ability to create goods in the digital realm and has accelerated the 'prosumer trend'. Moreover, increasing demand for product variety and customization, enabled by these new technologies, led to the breakdown of many mass scale industries, increasing the need for production strategies focused on individual customers (Da Silveira et al., 2001).

Table 1 - Pavitt Taxonomy of Innovation Patterns (Source: Kristensen (1999, p.4) adapted by the authors)

Sector type/ variables	**Supplier-dominated (SD)**	**Scale-Intensive (SI)**	**Science-Based (SB)**	**Specialised suppliers (SS)**
Firm size	Small firms	Large firms	Large firms	Small firms
Type of innovation	Processes	Processes	Mixed products and processes	Products
Locus of innovation	External	Production	R&D departments	Decentralised
Means of appropriability	Tacit knowledge	Tacit knowledge and entry barriers	Patents and entry barriers	Tacit knowledge/ reputation
Competitive parameter	Price	Price/ quality	Performance/ quality/ price	Quality/ performance

Studies highlight that not only manufacturing firms but also service firms can have differentiated patterns of innovation (Evangelista, 2000; Miles, 1993; Miozzo and Soete, 2001). Moving on from Pavitt's approach, a large amount of work has been carried out on the patterns of technological change in services. Miozzo and Soete (2001) proposed a service taxonomy, which directly extended the Pavittian approach into services. Even though this model brought the Pavitt taxonomy more up to date, there is still a weakness in the updated model in that we now understand the importance of users and open models of innovation in the service sectors. These do not appear in Miozzo and Soete's work and these factors are very significant to 3D printing.

Because of these limitations, we turned to Castellacci (2008) who offered an integrated classification of manufacturing and service sectors which encompasses the role of external players from the supply and design chains such as users and also the more open business models that are emerging today. This taxonomy contains four meta-categories: (i) Advanced Knowledge Providers, which includes specialised technology suppliers and science-based sectors such as software and specialised business services, laboratory and design services. (ii) Mass Production Goods, which includes the science-based and scale-intensive industries of the Pavitt taxonomy; (iii) Supporting Infrastructure Services, which includes network services which are dependent on information technology (IT) networks (e.g., banks, insurance and telecommunications), physical services that rely on physical networks (e.g., transport and travel services, and wholesale trade and distribution) and (iv) Personal Goods and Services which are 'backward' adopters of technologies (see Figure 4). The taxonomy is constructed by dividing the sectors along two dimensions. The divisions represent the position of the sector in the ecosystem as provider or recipient of the product and, similar to previous categorisations, the technological content of an industry.

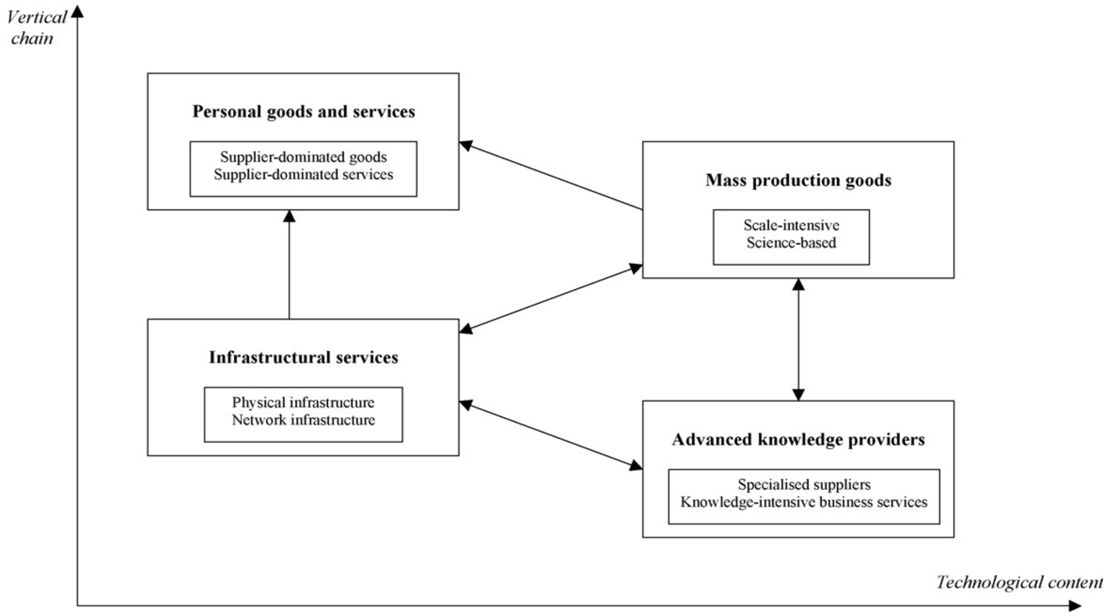

Figure 2 - A taxonomy of sectoral patterns of innovation in manufacturing and service industries (Source: Castellacci 2008, p.983)

Consumers have previously been involved in all stages of the production process and engaged in co-creation activities, from the design stage, to manufacturing and distribution stage but only to a limited extent (Rayna et al., 2015). 3D printing has enabled the increased participation of the user in the production process and has accelerated the co-creation trend (Rayna et al., 2015). The increased user participation in the production process blurs the line between consumption and production activities (Firat and Venkatesh, 1995). As Prahalad and Ramaswamy (2004) argue consumers should no longer be viewed as outside the firm.

Table 2. - Analytical Framework

Industry Type	Name of Taxonomy	Application Sector
Supplier- Dominated	Pavitt	Consumer Products
Scale -Intensive	Pavitt	Motor Vehicles
Science-Based	Pavitt	Aerospace/Defence Pharma/ Healthcare Consumer Electronics
Advanced Knowledge Providers	Pavitt/Castellacci	Knowledge Intensive Business Services Specialized Suppliers Online Platforms

In order to examine the veracity of the taxonomy, we identify more than 25 firms that were important exemplars of each of the industry configurations to map recent developments in 3D printing ecosystems against the typology. Factiva was the most useful source for this stage of the analysis, revealing hidden users of 3D printing (United States Government Accountability Office, 2015) not appearing in newspaper articles. We supplement the material with information from organization's websites, and generic 3D printing sources. The results are summarised in Table 3.

Table 3 - Framework Populated with Cases

Taxonomy	**Sector Type**	**Industry**	**Firm**
Pavitt	Supplier-dominated	Wearing apparel	Continuum Fashion Nakazato Van Herpen
		Jewellery, bijouterie and related articles	American Pearl
		Footwear	Adidas, Nike
Pavitt	Scale-intensive	Motor vehicles	BMW Ford Urbee
Pavitt	Science-based	Air and spacecraft and related machinery	Boeing, GE Aviation, NASA Lockheed Martin
		Medical and dental instruments and supplies	Hearing Aid Industry
		Pharmaceutical products	Johnson & Johnson
		Consumer electronics	Align Technology
Castellacci / Pavitt	Advanced Knowledge Providers	Knowledge Intensive Business Services	Aprecia New Normal
		Specialised suppliers	Autodesk Sketchup Turbosquid Stratasys 3D Systems Carbon DSM
		Online Platforms	Sculpteo I-materialise Quirky

The interest concerning 3D printing is well founded as there are many firms exploring its potential including digital technologies, as well as changes in manufacturing ecosystems (Rayna et al., 2015). However, for now the niches open to the technology have been making use of different features the technology offers and the use of 3D printing technology for the production of end use applications is a reality only for specific firms.

Findings and Conclusion

As expected, rapid prototyping and rapid tooling were placed within a traditional manufacturing process and featured in supplier-dominated, scale-intensive and science-based contexts. Our study shows that the use of 3D printing for direct manufacturing influences the level of disruption in different industries. Including Knowledge Intensive Business Services and online platform types in our model, we are able to explore wider areas than just traditional manufacturing. We noticed the major difference between using 3D printing as a production system or as an enabling technology for others in more recently evolved knowledge rich industries. The Knowledge Intensive Business Services type leads development by offering their customers tools and modelling systems which allow them to exploit their abilities in new areas or more effectively in existing ones. The online platform type represents the development of more open tools to be used in more innovative business models.

Our study highlights user involvement in production and the nature of co-creative. The level of direct manufacturing and customer empowerment in each industry will determine the competitive dynamics. Firms which can replace conventional manufacturing with 3D printing and introduce customers in the production process will encounter disruptive effects. Supplier-dominated industries use 3D printing to manufacture low volume customised products that are economically attractive, accelerating the do-it-yourself inventing and making (Anderson, 2012).

We feel that capturing a wide range of evidence on how 3D printing is being used allows us to develop a typology capable of explaining the many areas the technology can impact. Academics can use the typology to plot and build understanding of the mechanisms at work, whilst firms can explore the wider potential of the technology away from just as a direct replacement for existing production processes.

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