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reconfigurations

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The 3D Printing Order: Variability, Supercenters and Supply Chain Reconfigurations

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Structured Abstract

Purpose: Direct Digital Manufacturing (DDM) is conceived of as either disrupting the entire manufacturing economy or merely enabling novel production. Between these extremes, we introduce an alternative where DDM coexists with and complements traditional mass production. When multiple parts run across one manufacturing line, DDM can isolate variability associated with low volume part production and may be preferred to mass production despite being expensive. If DDM complements rather than cannibalizes mass production, this alters our understanding of who adopts DDM, the products built with DDM, and DDM's long-term supply chain implications.

Design/methodology/approach: This invited article explores a DDM rollout scenario and qualitatively assesses potential supply chain reconfigurations.

Findings: Our analysis recognizes that existing manufacturers with heterogeneous bills-of-material may develop DDM capabilities to isolate disruptive, low-volume production from scalable mass production. Developing DDM competence and raw material scale advantages, these manufacturers become the locus of change in a manufacturing landscape increasingly characterized by multi-product DDM supercenters.

Originality/Value: Extant research largely focuses on two potential reasons for DDM adoption: cost-per-unit and time-to-delivery comparisons. We explore a third driver: DDM's capacity to isolate manufacturing variability attributable to low volume parts. Relative to the extant literature, this suggests a different DDM rollout, different adopters, and a different supply chain configuration. We identify mass manufacturing variability reduction as the mechanism through which DDM may be adopted. This adoption trajectory would eventually enable a supply chain transition in which spare parts inventory migrates from finished goods at proprietary facilities to raw materials at generalized DDM supercenters.

Keywords: 3D printing, economies of scale, economies of scope, direct digital manufacturing, manufacturing supercenters, long tail

The 3D Printing Order: Variability, Supercenters and Supply Chain Reconfigurations

Direct Digital Manufacturing (DDM)¹ – 3D printing – may become a general purpose technology (Holmström & Partanen 2014) with wide-ranging implications for: supply chains (Eyers & Potter 2015; Ruffo, Tuck & Hague 2007; Holmström & Partanen 2014), market structure (Weller, Kleer & Piller 2015), sustainability (Chen et al. 2015), and production (Markillie 2012). “3D printing or additive manufacturing is a process of making three dimensional solid objects from a digital file. The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the entire object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object.” (<http://3Dprinting.com/what-is-3d-printing/>) The typical sequential phases include the digital design of the product (creation, modification, copying or scanning), the additive manufacturing process (i.e. the printing) and finishing.

While 3D printing will affect the economy, perceptions of the scope and magnitude of 3D printing’s implications are polarized. The popular press (Anderson 2012; Markillie 2012; Winnan 2012) optimistically conceives of 3D printing as a new “industrial revolution,” a “gold rush” that will dramatically change supply chains, firm strategies, competition, and industrial geographies. In contrast, the academic literature largely confines 3D printing to specialized situations (Holmström et al. 2010; Pérès & Noyes 2006), and particular and complex products (Holmström & Partanen 2014). Technological limitations, high material costs, lack of safety and quality standards, and high energy costs (Berman 2012) further confine 3D printing applicability.

¹ Direct digital manufacturing is also commonly called 3D printing. We use both interchangeably. The literature has also used the terms “additive manufacturing” and “rapid manufacturing.”

We propose a middle-of-the-road scenario where manufacturers with complex bills-of-material will adopt 3D printing to extract additional scale advantages from traditional manufacturing. Hence, product variability, in addition to product launch (Khajavi et al. 2015) is a pivotal antecedent for the co-location of traditional manufacturing and DDM. Demand for specialized products and demand from specialized geographies will reduce 3D printing's raw materials costs (Ruffo, Tuck & Hague 2007), and advance 3D printing technology. We propose that resulting cost reductions and quality improvements will make 3D printing viable for urgent, otherwise disruptive production in existing manufacturing facilities. Manufacturers will allocate expedite orders for low and sporadic demand parts to 3D printing, reducing setup and changeover on traditional production lines.

3D printing-adopting manufacturers will imprint early 3D printing technological development and further reduce raw material costs. These co-located manufacturers may develop their 3D printing competence as on-demand producers of a variety of products, satisfying local demand for out-of-production and long lead time parts. If they can achieve 3D printing economies of scale through raw materials and competence, this on-demand production will emerge as a new business segment where existing manufacturers hybridize OEM and contract manufacturing. Concentrated, colocated 3D printing production will lead to 3D printing supercenters – facilities that concentrate low volume, customized, and high urgency production.

This invited, conceptual paper first discusses the economic rationales for contemporary manufacturing and for 3D printing. We then propose a process where 3D printing supercenters will emerge and highlight some of the supply chain-related benefits of 3D printing supercenters. Finally, we discuss implications for supply chain practice and reconfiguration.

Background

Two fundamental processes, increasing manufacturing scale (Chandler 1962) leading to high manufacturing concentration and fine-slicing of global value chains (e.g., Buckley & Strange 2015) drove two centuries of global economic change. Characterized by large-scale manufacturing, extensive long-distance distribution, and multi-stage production, the current global economy reflects these origins.

The industrial revolution and technological advances during the 19th and 20th centuries leveraged economies of scale and scope to reduce both average unit costs and lead times (Chandler 1997; Chandler 1962). For example, automobile production time fell from 12 hours and 8 minutes in 1913 to 1 hour and 35 minutes in 1914 (Chandler 1997: 77). Economies of scale and scope also concentrated economic activities (Chandler 1962). For example, in 2007, the four largest firms in the American household vacuum cleaner manufacturing industry controlled 70 percent of total sales and the largest eight controlled 96.3 percent. In the American brewing industry exclusive of brewpubs and microbreweries, the number of breweries fell from 2474 in 1880 to 45 in 1980 while the four-firm concentration ratio increased from 11 percent to 86 percent between 1935 and 1989 (Carroll & Swaminathan 1992).

Recently, liberalized international trade and investment, financial market deregulation, and advances in information and communication technologies encouraged global relocation of economic activities (Buckley & Strange 2015). In this increasingly fluid global economy, firms located activities to optimize labor costs, raw material access, infrastructure access, etc. Regional and national economic specialization finely sliced manufacturing value chains, increasing global trade. According to the World Trade Organization, in 1970, global exports totaled \$0.3 trillion. By 1990, total exports were over

10 times larger (\$3 trillion), doubling by 2000 (\$6 trillion), and doubling again by 2007 (\$14 trillion). At \$19 trillion, current exports are 60 times their 1970 value.

Exports' exponential growth also marks a redistribution in terms of who exports and how much. "Global supply chains have transformed the world. They revolutionized development options facing poor nations; now they can join supply chains rather than having to invest decades in building their own. The offshoring of labour-intensive manufacturing stages and the attendant international mobility of technology launched era-defining growth in emerging markets ... This reversal of fortunes constitutes perhaps the most momentous global economic change in the last 100 years." (Baldwin 2014: 13). From 1985 to 2012, advanced economies' share of global exports decreased from 70.1 percent to 53.6 percent while emerging economies' share increased from 18 percent to 33.5 percent (Buckley & Strange 2015, p. 241 data from UNCTADSTAT).

This changed global economic structure. Manufacturing's share of global economic output has been falling steadily. In the U.S., manufacturing activities are responsible for only 12.4 percent of valued added in the economy, down from 16.4 percent in 1998 (The World Bank, 2015). Similar changes have occurred in other advanced economies such as Italy (from 20.3 percent to 15.5 percent), U. K. (17.6 percent to 9.4 percent). Worldwide estimates, report a reduction from 19.5 percent in 1998 to 16.5 percent in 2010. The fine-slicing of the value chain enables off-shoring, explaining manufacturing's decreasing importance. As shown above, emerging economies conduct more manufacturing activities hence reducing the relative importance of manufacturing in advanced economies.

These processes have affected supply chain structure and complexity. Raw materials, semi-fabricated materials, components and final products travel longer distances from suppliers to customers, change hands more frequently, and cross multiple organizational and national boundaries. With the fine-slicing of the value chain, coordination requirements grew

exponentially, increasing supply chain complexity and driving supply chain innovations (e.g., just in time and lean manufacturing, advance shipment notices).

3D printing

Economics of scale and scope and the fine-slicing of the global value chain dominate the rationale for traditional manufacturing. In sharp contrast, 3D printing significantly reduces established scale and scope advantages and the need to divide the value chain across various localities. Hence, 3D printing has the potential to return manufacturing jobs to wealthy counties, which have experienced a decline in the share of manufacturing for several decades (Markillie 2012).

Contemporary literature focuses on the applicability of 3D printing to spare parts (Holmström et al. 2010; Holmström & Partanen 2014; Pérès & Noyes 2006), products demanded by systems that are difficult to access due to distance (e.g., the International space station), time (obsolete parts), danger, (disaster struck areas) (Pérès & Noyes 2006) and complex products (Holmström & Partanen 2014; Gress & Kalafsky 2015). Although 3D printing is emerging as a viable alternative for low volume and customized manufacturing (Eyers & Potter 2015; Eyers & Dotchev 2010), Gress and Kalafsky (2015) estimate that currently 36.5 percent of all 3D printing globally is prototyping.

This restrictive applicability view is motivated by material costs and technological limitations. Berman (2012: 161) argues that “high material costs currently limit the use of 3-D printing to applications that are high value, and/or when speed or privacy is critical”. The lack of printing precision, colors, surface finishes and limited materials (Berman 2012) further restricts 3D printing utilization, confining it to very particular situations (Holmström et al. 2010).

Notwithstanding these limitations, the extant literature has identified numerous economic benefits of 3D printing that originate from: elimination or simplification of

production stages, availability of new products requiring new supply chains, and changes in recycling and waste value chains.

3D printing reduces tooling requirements (Eyers & Potter 2015), affecting lead times and the need for amortization of tooling costs across a large number of components (Ruffo, Tuck & Hague 2007). 3D printing also reduces: inventory holding, part obsolescence and shortages (Holmström & Partanen 2014), packing and packaging (Berman 2012), assembly work (Weller, Kleer & Piller 2015; Tuck, Hauge & Burns 2007), the need to develop production processes in the product development stage (Gibson, Rosen & Stucker 2010), setup costs, and changeover time (Tuck, Hauge & Burns 2007). Furthermore, for complex parts that require multiple components, tooling and pre-chain setup, energy use may be lower than for injection molding (Chen et al. 2015).

3D printing also allows innovative products requiring new supply chains because it allows for otherwise impossible configurations (Gress & Kalafsky 2015) like complex geometric parts (Hague, Mansour & Saleh 2004; Gibson, Rosen & Stucker 2010). 3D printing also shifts the basis for competition for quality. “Quality of the final product will be dependent on the CAD model and not necessarily on the production process” (Ruffo, Tuck & Hague 2007: 28). Finally, 3D printing may positively impact sustainable development, amending the composition, length and complexity of waste and recycling value chains (Chen et al. 2015).

Relative to economies of scale and scope based traditional manufacturing, 3D printing further redistributes production, reduces lead times through instantaneous production and commoditizes production allowing for the rental of commoditized manufacturing units. Traditional manufacturing activities become concentrated due to economies of scale and scope and the fine-slicing of the value chain. Concentration necessitates longer distance between the localities of demand and supply. Economies of scale and scope provide the

economic rationale for this divide. 3D printing creates the conditions to substantially shrink supply chain distance (Anderson 2012; Holmström & Partanen 2014). At the extreme, in the case of home 3D printing, supply and demand co-occur. In industry, firms will produce missing, lost or broken parts on-site instead of waiting for distant suppliers to produce and ship (Gibson, Rosen & Stucker 2010; Holmström et al. 2010; Pérès & Noyes 2006). In cases where products require ex-post work, (e.g., assembly, fitting, packing) the distance will fall from thousands of kilometers and complicated logistics to local/regional production and short-distance logistics.

Similarly, concentration and fine-slicing of the supply chain contribute to long total cumulative lead times, temporally isolating demand from supply. This temporal separation of demand from supply generates complex planning error, for example in demand forecasting and capacity scheduling. Such time-related uncertainties create inefficiencies including over-production, safety stocks, and service loss. 3D printing allows for almost simultaneous production and consumption (e.g., Berman 2012; Gibson, Rosen & Stucker 2010; Anderson 2012). Home 3D production will reduce the time lag between starting production and consumption to printing time. Local or regional 3D printing will reduce finished good delivery time, mitigating safety stock requirements.

Perhaps the most exciting consequence of 3D printing is that it commoditizes manufacturing infrastructure (e.g., Holmström et al. 2010). More than 23,000 3D printers from Hawaii to Mozambique to Japan are available for local, custom printing (<https://www.3dhubs.com/>). There are nine 3D printers around Birmingham, Alabama; seventy around Atlanta; and sixteen in Trenton, New Jersey. In the U.S., there are over 4,500 printing hubs connected to the 3dhubs.com platform only. For comparison, According to the U.S. Bureau of Economic Analysis, there are only 234 footwear manufacturers in the U.S. Such 3D ecosystem will increase user innovation and user entrepreneurship (Piller, Weller &

Kleer 2015). However, 3D printing has not yet reached critical mass, and the exponential growth in households printing is still to come.

The benefits of the commoditization of manufacturing infrastructure extend beyond the home 3D printing context. With commoditized manufacturing infrastructure, we will observe both the instantaneous rental of manufacturing infrastructures and the creation of a market for manufacturing infrastructure. A point that we will develop further below, the commoditizing of manufacturing infrastructure will allow firms that invest in developing 3D printing capabilities and capacity to increase capacity utilization through on-demand printing to other firms and individuals in the vicinity of the manufacturing site. Finally, if demand for printing center A exceeds its manufacturing capacity, manufacturing orders will be redirected to center B (as long as the additional distribution costs from center B are lower than customer queuing costs). This process operates in the same way that a search engine redirects customers from fully booked hotels or flights to alternative providers.

From Long Tail to DDM Supercenters

The long tail thesis (Anderson 2006; Anderson 2012) recognizes that, in many markets, the number of available products or services is typically only a small percent of the total number that could be offered. “Every retailer has its own economic threshold but they all cut off what they carry somewhere. Things that are likely to sell in the necessary numbers get carried; things that aren’t, don’t.” (Anderson 2006, p. 20). For example, Andersen (2006) finds that while Walmart had up to 25,000 songs available in physical form, Rhapsody’s customers had access to 1.5 million digital songs in December, 2005. While hits were sold at Walmart and downloaded more frequently than any other single song at Rhapsody, 40 percent of downloads by Rhapsody’s customers were of songs ranked below 25,000. Popular and widely available products or services constitute the head of a power law distribution and numerous hard-to-find or unavailable products exist at the tail. Figure 1 depicts this power

law distribution. Products at the head like books at bookstores are depicted on the left hand side of the figure. The internet made the tail of the distribution, depicted on the right hand side of the figure, much more visible and economically viable. For example, Google finds and facilitates access both to the head (daily news and gossip) and the tail (e.g., sheet lamination discussions, a 3D printing technology).

INSERT FIGURE 1 ABOUT HERE

3D printing provides the conditions where the number of available physical products may increase by several orders of magnitude. Similar to the manner that EBay created a platform for used goods, Amazon created a platform for less commonly purchased books, and Google created a market for less commonly sought information, 3D printing creates a market for less commonly demanded manufactured goods (Berman 2012; Gibson, Rosen & Stucker 2010; Holmström & Partanen 2014; Pérès & Noyes 2006). Yeggi offers a cross-community (e.g., MyMiniFactory, CGTrader, Pinshape, and Thingiverse) search engine for printable 3D models for an ever-increasing number of products (e.g., sandals, miniature cars, keys holders, kitchenware, and iPhone cases) developed by 3D users (Piller, Weller & Kleer 2015; Anderson 2012).

In Anderson's (2006; 2012) long tail conception and the extant literature (Holmström et al. 2010; Holmström & Partanen 2014; Pérès & Noyes 2006), DDM enables tail production such as out-of-production replacement parts, customized gifts and usable prototypes. However, high unit costs make mass production much more economical for production within the head of Anderson's scheme. For example, the authors interviewed a mid-sized U.S. industrial equipment manufacturer, RiverCo, which tested DDM on an \$8, complex machined metal part. The result was out-of-spec and \$800. Energy alone cost \$400.

From RiverCo's initial DDM test, we might conclude that DDM is forever relegated to tail production of high cost, mission critical spare parts and one-off novelty items (e.g., Pérès & Noyes 2006). But RiverCo's supply chain manager has requested new and ongoing tests. According to her, engineering tested the wrong part type and used insufficient evaluation criteria. At the supply chain manager's request, RiverCo will conduct a new test on a simple, low volume, plastic part. And interestingly, RiverCo will not confine their DDM assessment to cost comparisons.

We suggest that RiverCo's experience raises a hitherto unexplored DDM rollout scenario, one in which hobbyists lower costs and contribute to technological advancements to the point where existing manufacturers invest in DDM to fulfill internal spare parts requirements and complement traditional mass production. This DDM deployment creates further scale for DDM raw materials, as suggested by Berman (2012) and Holmström and Partanen (2014), and builds DDM competence among early adopters (Dierickx & Cool 1989). This enables further manufacturing of simple, capacity consuming parts. This will be particularly true in complex manufacturing operations with significant part heterogeneity.

Relative to traditional manufacturing, DDM presently suffers from two significant cost disadvantages: high energy and raw material costs. Despite these cost disadvantages, DDM may still have extensive application in traditional manufacturing environments. The extant literature (Gibson, Rosen & Stucker 2010; Holmström et al. 2010; Holmström & Partanen 2014) recognizes that DDM will grow to satisfy Anderson's (2006; 2012) long tail. As this happens, DDM raw material manufacturers will benefit from increasing scale, pushing raw material prices down and extending the range of cost viable DDM production. In that way, increasing DDM adoption/utilization will enable increasing DDM adoption/utilization.

As DDM production costs fall and precision increases, we expect to see four areas grow. Hobbyists and specialty firms will continue to build out the tail, production which may occur within 3PLs (Holmström & Partanen 2014). DDM will support mission critical applications in remote or hostile environments such as submarines and space stations (Pérès & Noyes 2006). Geographies with high concentrations of custom capital equipment will invest in DDM to satisfy pooled spare parts requirements. Airports and ports, for example, will likely have DDM to replace parts on-demand.

Finally, existing large and mid-sized manufacturers will invest in DDM for three reasons. Hybrid production is more cost efficient at the product launch stage if the product does not succeed in the first attempt to penetrate the market (Khajavi et al. 2015). Large manufacturers with extensive capital stock may invest in DDM to produce spare parts for on-site use. A Boeing plant or an Alcoa refinery, for example, may invest in DDM instead of an army of machinists (Holmström et al. 2010; Holmström & Partanen 2014; Wooten 2006). Mid-sized manufacturers with heterogeneous product lines may invest in DDM to reduce spare parts inventory, improve customer service, or reduce plant variability, three criteria absent from direct cost comparisons.

The development of DDM expertise within existing manufacturing firms, and the consequent development of DDM technology to support existing manufacturing, has major implications for the long-term coevolution of DDM and traditional manufacturing. DDM enables new products and on-site production. Manufacturing's gradual adoption of DDM for low volume parts production and for product launch (Khajavi et al. 2015) may be vital antecedents of the penetration of DDM into traditional manufacturing.

Rather than competing with DDM, manufacturers may use DDM to extract even greater scale from mass production. Co-locating these two manufacturing processes, as depicted in the middle section of Figure 1, will reduce production line setups, freeing up

valuable production capacity. Manufacturers will eventually find an approximate internal equilibrium between traditional manufacturing's scale advantages and DDM's setup cost advantages. Lower volume parts with highly disruptive setups will favor DDM, regardless of relative cost, and high volume parts will favor traditional manufacturing.

Comparing cost-per-unit between DDM and traditional manufacturing is insufficient when considering the optimal technology.² Low volume parts can be highly disruptive in a factory in which multiple parts share the same production line. DDM cost per-unit comparisons include production cost and setup cost, but they do not include opportunity cost for the production line or the second setup. Suppose that a factory is producing 4,000 units of a complex assembly involving 500 piece parts. Subassemblies are running across 5 different production lines. An urgent order comes in for 10 units of a spare part. That part is scheduled to run in 6 weeks, but we decide to run it today. To run the part, we must shut down one subassembly production line, incur a setup, and then incur a second setup back to the subassembly. Only the first setup is included in the spare part's standard cost. The extra subassembly setup appears as a variance influencing the subassembly's standard cost. The other four subassemblies were already complete, possibly transferred to a warehouse for storage, and pulled for final assembly only after the production interruption. The production interruption causes:

1. An extra spare part setup
2. An extra subassembly setup
3. Delayed assembly completion
4. Increased assembly/subassembly safety stock to accommodate lead time variability

² Also note that increased DDM utilization will compromise some scale advantage from traditional manufacturing. For example, suppose a manufacturer produces 100 units per year in a single 100-unit lot. The standard cost for that part is computed by allocating a single setup across 100 units. Now suppose that the same manufacturer uses DDM to produce 20 units for an expedite request. The standard cost for traditional manufacturing increases because a single setup is now allocated across only 80 units. Increasing internal DDM utilization will alter manufacturers' standard costing to favor DDM.

5. Short-term warehousing of completed subassemblies
6. Delay of every subsequent production order running across the production line

Costing methods typically capture (1), but do not measure (2-6). Using DDM for highly disruptive parts, even if they are several orders of magnitude more expensive than mass production, may be worthwhile when that allows the remainder of the plant to run more stably. If a spare part costs \$1 to mass produce and \$1000 to print, the \$999 may still be worthwhile. This will be particularly true for manufacturers with many parts, heterogeneous manufacturing orders, and a legacy install base requiring low volume spare parts production.

Removing low volume, disruptive parts from regular production sequencing, DDM adoption can grow within existing manufacturers by complementing mass production's scale. Manufacturers will probably invest in DDM to satisfy spare parts sales requirements. Initially, because of cost and precision, they will likely invest in plastics DDM. Though only a small portion of overall manufacturing, this may quickly dwarf total hobbyist DDM activity, and will likely lead to technological advances that further reduce raw materials costs and energy consumption across DDM applications. In response, manufacturers will roll out DDM for more complex and demanding materials such as metals and composites, maximally pushing plant variability to setup-free DDM.

Incorporating those arguments with Anderson's (2006; 2012) conceptualization of head and tail in production, the long-term evolution of DDM and mass production technologies will be like this. Mass production will dominate the head (popular and widely available products such as galvanized framing nails, residential door hinges) depicted at the left hand side of Figure 1. Occasionally, similarly to viral videos on YouTube, a DDM-produced part will be printed by many individuals for immediate consumption before the trend dies off or is converted into a traditional manufacturing process. DDM will dominate the tail (custom medical implants or out-of-production parts, etc.) depicted on the right hand side of Figure 1,

while some highly specialized items will require traditional manufacturing (e.g., forged parts for marine engines and hydro dam turbines).

Outside the extremes of the head and tail (depicted at the center of Figure 1), manufacturers will vary in the degree to which they utilize both technologies. Once a year, a factory might run an EOQ for a gasket required to support an install base. But if the factory is backordered without scheduled replenishment, they will produce the gasket using DDM. Manufacturers with heterogeneous product mixes and deep bills-of-material are most likely to invest in such co-location of DDM and mass production.

While DDM may remain a small fraction of total production in this portion of Anderson's power law, at least until a technological breakthrough occurs, manufacturers' DDM use here will probably dwarf DDM utilization in the tail. Consequently, existing manufacturers will probably drive DDM technology forward. DDM will advance to solve manufacturing's problems, and manufacturers will disproportionately develop DDM competencies and scale. As existing manufacturers develop their internal DDM competences and scale, this will yield commoditized manufacturing opportunities. For example, a mid-sized manufacturer in Gary, Indiana might develop DDM competence to produce spare parts. Why not parlay that expertise as a generalized, expedited parts producer for Midwest applications? If GE Aviation has a parts-emergency at O'Hare, the Gary facility can satisfy that demand in hours. If a train operator requires an out-of-production spare part, a heterogeneous manufacturer already invested in DDM can provide that to a 3PL very quickly.

Because DDM is setup-free, existing manufacturers that invest in DDM may satisfy other manufacturers' local demand. These manufacturers will accrue learning and competence advantages, and enjoy economies of scope from common raw materials. Thus, they should emerge as cost leaders relative to DDM producers focusing exclusively on long tail products. Such manufacturers will be in pole position to develop as multi-product

producer supercenters satisfying both local spare parts requirements and local demand for custom goods. Manufacturers will likely come to see this multi-product producer role as a distinct strategic capability.

Supply Chains and DDM Supercenters

The emergence of DDM supercenters will trigger manufacturing changes. In particular, we discuss DDM supercenters and manufacturing stages, and inventory reconfigurations. The current manufacturing configuration includes five general stages: extraction/collection, refining, fabrication, assembly, and retail. Extraction/collection includes mining, oil extraction, scrap collection, etc. Refining refers to the process of rendering inputs generalizable. For steel, this is the process of reducing iron ore and scrap metal to molten slag. Fabrication converts infinitely divisible inputs to countable outputs of consistent dimension (e.g., converting molten slag into 4x8 steel sheet, or petroleum products into plastic pellets). Assembly combines inputs of standard sizes and consistent material, and retail is a stocking location for customer retrieval. To the extent that recycling occurs, end-users may send material back to the extraction/collection phase.

With printers capable of managing only one material at a time, we expect several substantial supply chain configuration changes. First, the refining stage will be integrated, either forward by extraction/collection or backward by fabrication. This already occurs in the steel industry, where mills smelt scrap and ore to fabricate finished steel products. Imagine, for example, a firm that collects scrap steel, aluminum, copper, etc. for conversion into a powder or pellet form usable by printers. The integration of the refining phase and the standardization of printer inputs will enable printing supercenters capable of leveraging raw material economies of scope.

Further, with printers capable of simultaneously printing in multiple materials (e.g., the Multifab 3D-printer: http://www.csail.mit.edu/multifab_multimaterial_3D_printer), some

assembly will eventually disappear. Staged, multi-material printers will build even complex finished goods in layers. A printer will use wood chips to print a box. Then the printer will use plastic beads to print a small plastic tub, which it will fill with screws printed from powdered steel, and cover with a paper backing printed from more wood chips. When the printer can simultaneously print porcelain, aluminum, steel, and glass, it will print spark plugs. Eventually, maybe a printer could print a cylinder head with the spark plugs in place. Following the same logic as the single material printing, assembly operations for low volume parts will increasingly occur in larger and larger printing complexes –supercenters with no asset specificity and zero changeover costs. Supercenters will benefit from economies of scope in learning, technological competence, and raw materials purchasing.

Existing manufacturers' development of DDM into on-demand, multi-product supercenters will significantly influence global supply chain inventories. As manufacturers reallocate low volume part production to DDM, they will correspondingly reallocate finished good inventory investment to DDM raw material inventory, potentially reducing plant-level aggregate inventories. As some manufacturers increasingly develop their DDM capabilities to serve other manufacturers' low volume production needs, the DDM-emphasizing plants will expand raw material inventory. This raw material increase will be more than offset by a corresponding fall in the outsourcing manufacturers' finished goods inventories. Economies of scope for raw materials will exacerbate this, pushing low volume finished goods inventory toward DDM raw material inventory at regional supercenters.

High volume parts may be even more affected. For high volume parts that remain mass-produced, removing low volume, disruptive parts from production lines will reduce production costs and lead times. Expedited low volume orders interrupt scheduled manufacturing orders, triggering extra setup. This variability inflates standard costs and average order completion times, consequently reducing lot sizes and increasing safety stocks.

Reducing production variability consequently increases mass produced parts' lot sizes and reduces the same parts' safety stocks. Increased lot sizes further reduce aggregate setup costs, enabling cost reductions on mass produced parts.

The co-location of mass production and DDM leads to the interesting contrast that high volume parts' production costs will fall while low volume parts' production costs will likely increase. Global manufacturing inventories will rebalance. High volume parts' lot sizes will grow and safety stocks fall, and standard costs will fall, leading to an ambiguous inventory outcome. Low volume parts' lot sizes and safety stocks will both fall, and these will fall more than the requisite supporting increase in DDM raw material inventory.

Discussion

Our arguments are specifically relevant to supply chain managers who have yet to fully consider, let alone embrace, 3D printing technologies. The 2015 McKinsey survey of leading manufacturers reveals that 40 percent of respondents are not familiar with additive-manufacturing technology "beyond press coverage" (Cohen, George & Shaw 2015), 5 percent dismissed it as irrelevant for them, and 12 percent think that they need to learn more. Only 10 percent of manufacturers perceive the technology as relevant for them today. The distribution of opinions is very typical for an emerging technology (Allen 1988; Economides & Himmelberg 1995). 3D printing has been around for over three decades but has only recently shown signs of technological breakthroughs and of accelerated diffusion by both businesses and households accelerated by the loss of patent protection of some core 3D printing technologies.

Manufacturers of heterogeneous products are in a unique position to develop DDM competences and capabilities as a byproduct of investment in increasing the efficiency of their traditional manufacturing operations. Early investment in DDM may allow such manufacturers to grow into regional supercenters. Based on CIMO-logic (Denyer, Tranfield

& van Aken 2008), introducing DDM (intervention) can mitigate production variability (mechanism) for manufacturers with heterogeneous products and complex bills-of-material (context), thereby improving mass production efficiency and developing DDM-based service manufacturing businesses (outcome).

To realize the potential of DDM for mass producers whose customers will demand rapid delivery of specialized or spare parts, they need to digitize and publish searchable, printable component files. The availability of such print files will ensure component quality, compatibility with other components and product safety. The alternative is to let the 3D community produce replicas from 3D scanning or third-party replacement designs resulting in varying levels of quality, compatibility and safety. This will also accelerate the growth of DDM supercenters.

In 2009, 3D technologies such as stereolithography lost their patent protection. Consequently, many new firms (e.g. HP) entered the market traditionally controlled by patent-holders such as 3D systems and Stratasy. Incumbents and new entrants have been rapidly innovating printing technologies and the range of materials that printers can use. However, the 3D printing stock index, including firms such as, 3D Systems Inc. (DDD), Stratasys Ltd. (SSYS), The ExOne Company (XONE), Organovo Holdings (ONVO), Arcam AB (AMAVF) (ARCM.ST on Nasdaq OMX) and voxeljet AG (VJET), has declined sharply, from 100 in October 21, 2013 to 38.69 on July 2, 2015 (see <https://3Dprintingstocks.com>).

This is not surprising in an emerging high technology industry with multiple technologies and no apparent standard. These firms and those who will soon enter compete on innovating the technology of tomorrow. In the quest for legitimizing both the firm and the technology, most will not succeed (Carroll & Swaminathan 1992; Carroll & Delacroix 1982). The proliferation of technologies (e.g., vat photopolymerization, material jetting, material

extrusion, powder bed fusion (see: ASTM 2013: 1)), will lead to more innovative solutions across an increasingly diverse range of materials and material combinations.

We explore production variability as a driving force leading to the co-location of traditional manufacturing and DDM. Future research should identify additional antecedents for the colocation of traditional manufacturing and DDM beyond production variability and product launch (Khajavi et al. 2015). Future research should provide cost comparisons between manufacturers with high production variability using traditional manufacturing only and those that use hybrid manufacturing (traditional manufacturing and DDM). Such research can utilize the methodology employed by Khajavi et al. (2015) with respect to product launch. A related avenue for future research involves simulation studies that explore the extent of penetration into the manufacturing sector of DDM supercenters depending on different achieved levels of their economies of scope and scale.

In summary, rather than completely reshaping the manufacturing landscape or being confined to niche consumer goods, we propose a blended scenario where manufacturers with complex bills-of-material adopt 3D printing early to isolate production variability. Over time, those manufacturers will develop 3D printing competences, enabling them to produce on-demand for other manufacturers and individuals. Emerging as regional 3D supercenters, these manufacturers will concentrate low volume production, exchange finished good inventory for undifferentiated DDM-compliant raw material inventory, and ironically facilitate additional mass production scale.

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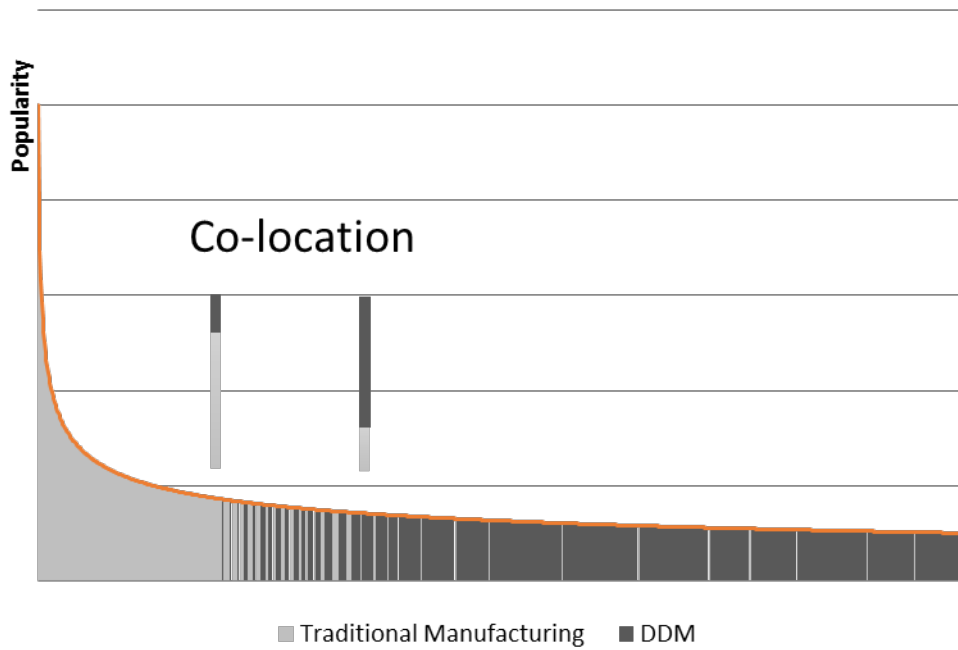
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Figure 1: Production technology by product popularity*



*Adapted from Anderson (2006). The figure depicts the power law of product popularity divided by manufacturing technology. As the number of products demanded decreases, DDM becomes more prevalent. In the middle both technologies co-exist and when high product variability exists, the co-location of both technologies, indicated by the scales above the middle section of the figure, within the same facility will occur.