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**EXPLORING THE MAKER-INDUSTRIAL REVOLUTION:
WILL THE FUTURE OF PRODUCTION BE LOCAL?**

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Exploring the Maker-Industrial Revolution: Will the future of production be local?¹

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Draft: Comments Welcome

Introduction

Many believe that modern technologies such as 3D printers, sensors, and networking capabilities provide an unprecedented opportunity to support a renewal of localized production— especially when combined with “Maker Movement” trends toward customization, user engagement, local and small-batch production, and reparability. Others are unconvinced, and instead forecast increased efficiency in high volume production and global supply chains. Let us state the core questions: will either the Maker Movement or these dramatic new technologies fundamentally influence the basic structures of market competition? Or, will this all be merely an interesting but marginal blip along the road as the technologies themselves are absorbed into automated high volume production? What are the clues? What do decision-makers across industry and policy need to know in order to properly evaluate this potential?

With this paper, we look beyond the revolutionary rhetoric of the Maker Movement in an attempt to consider its effects on a more practical level. We define the Maker Movement (also known as the Do-It-Yourself or Fab Movement) as a crusade for more accessible design and creation— incorporating a mix of new technologies, philosophies, and business models. This Movement is especially tied to the concepts of digital fabrication, public access to tools through community workshops (Fab Labs, hackerspaces, makerspaces, repair cafés, TechShops, etc.), the Internet of Everything/interconnected devices, and Jeremy Rifkin’s concept of the “zero marginal cost society.” We employ a vague definition here because the concept itself is nebulous and ill-defined; depending upon whom one asks, this Movement is a “bourgeois pass-time,” the “new industrial revolution,” the future of interdisciplinary education, the impetus for a wealth of new hardware startups, and/or yet another overhyped and impossible vision of techno-utopia.²

This essay will focus upon whether or not the Maker Movement might substantially disrupt traditional manufacturing, or alternatively at least create an enduring niche

¹ Appendix 1 provides a compendium of academic and mass-media resources on the Maker Movement.

² Maxigas and Peter Troxler, “Digitally-Operated Atoms vs. Bits of Rhetoric: A Mash-Up,” *Journal of Peer Production*, no. 5 (October 2014), <http://peerproduction.net/issues/issue-5-shared-machine-shops> .

position in evolving manufacturing. Part I examines this from three perspectives: (1) Redistributed Production, (2) Personalized Fabrication, and (3) After-Market Repair and Customization.

The idealistic devotees of the Maker-Industrial Revolution argue that the particular confluence of Maker ideas and technology will lead to a hybrid form of production, combining the scale and efficiency of high-volume manufacture with the benefit to local economies provided by small, artisanal businesses. We divide these idealists into the Trekkies³ who imagine a thoroughly radical and (we will argue) science fictional manufacturing revolution, and the moderates who foresee significant changes but not a complete overhaul of the current manufacturing paradigm. We are focusing here on the “moderate Trekkies.”

By contrast, there are a group of skeptical realists who recognize possibilities, but consider that the impact of the tools and the Maker Movement will be more restrained. They tend to step past the Maker rhetoric around “democratization,” doubtful that this is an attainable or reasonable objective. Skeptical realists argue that, despite some impact on marketing strategies, products, and factory tools, the Maker Movement will not lead to radical changes in systems of production or current power structures; 3D printers, other digital fabrication tools, and open-source technologies have already been in use for decades without forcing any substantial shifts to production models. High-volume manufacturers already produce small batches of customized pens and T-shirts featuring company logos, so skeptics believe that the addition of more complex, customizable elements would likely follow the same traditional manufacturing model. Although many new micro-enterprises have arguably emerged as a direct result of the Maker Movement and related technologies, the skeptics don’t believe that the cumulative effect of these businesses will significantly affect the current high-volume manufacturing paradigm—which, by most calculations, is extraordinarily cost-effective for both consumers and corporations.

These skeptics may still be fervent believers in the overall potential of the Maker Movement—they simply don’t buy into the idea that this Movement and related technologies will itself drive substantial shifts in the current production landscape.⁴ Compelling evidence from the entrepreneurial community indicates that this Movement has had a significant impact upon both artisanal businesses and more ambitious

³ *Trekkie*: nerd vernacular for “Star Trek fan”

⁴ Many researchers (see Appendix 1) have provided excellent evidence for the positive impact of the Maker Movement upon education, and its success in empowering the general populace to regain their agency over increasingly black box technology. The psychological “Ikea effect” describes how Makers often value their self-created objects much higher than equivalent store-bought versions. Idealists may identify this phenomenon as indicative of a widespread mindset shift from passive consumption toward more active creation, yet there is little economic evidence of any market impacts outside of high-end consumers—even with the advent of easier and more affordable digital fabrication tools in households and across over 3000 publicly-accessible community workshops.

hardware startups⁵—and yet the skeptic would point out that, as Maker-entrepreneurs scale up their startups, they tend to follow traditional paths of either high-volume manufacturing or boutique artisanship. For example, the New York-based company MakerBot, once heralded as a pioneer in “democratizing manufacturing” through their affordable 3D printers, recently moved all their own production to China. (There are, however, regional desktop 3D printer competitors that kept their local production—such as Ultimaker in the Netherlands and Type A Machines in California.) Given the ease of high-volume manufacturing and economies of scale, the skeptic would argue that many Maker startups will either follow MakerBot’s less-than-revolutionary lead or else remain small and non-competitive.

I. The Maker-Industrial Revolution: Visions, Possibilities, and Realities

1. *Redistributed Production*

The Maker-Industrial idealist envisions a world of agile, networked micro-factories, similar to pre-industrial cottage industries yet employing the latest in state-of-the-art manufacturing technologies. Although the term “distributed manufacturing” has also become popular among academics, we employ the term “redistributed” here to distinguish the concept of micro-factory concept from geographically-distributed production, such as the traditional distributed model for iPhone manufacture. Advocates of redistributed manufacturing refer to how printers and later the internet effectively “democratized” publishing, allowing anyone access to write, read, and share their ideas in a new way. Redistributed micro-factories, idealists argue, will bring manufacturing capabilities back to the people at a local level, disrupting the current global model of high-volume production and international supply chains while decentralizing ownership structures.

It is important to separate the potentially-viable model of large-volume localized production through interconnected Small and Medium Manufacturers (SMMs) from the Trekkie utopia of large-volume *personalized* production, consisting of many independent artisanal and/or household shops.

Both idealists and skeptics in the promise of the Maker Movement would agree that small-batch production and agile factory configurations are now easier than ever before, thanks to advances in software and digital fabrication. With the advent of “smart,” internet-connected sensors and controls, factories will also become more digitally

⁵ The Maker Movement’s impact upon entrepreneurship is four-fold: facilitating pilot projects on crowdfunding platforms like Kickstarter, substantially decreasing the cost of prototyping and small-batch manufacturing, encouraging the open-source sharing of new ideas, and fostering ecosystems to support entrepreneurs. Again, see Appendix 1 for more details.

networked and less dependent upon controllers who must be physically present. For the first time in the history of manufacturing, state-of-the-art Computer Numeric Control (CNC) machines programmed to mill, cut, and/or 3D print are affordable and relatively easy to employ for both personal and SMM applications. Desktop 3D printers can cost under US\$1000, and the graphical interfaces of modern machining software provide a much lower barrier to entry than CNC machines of the past decades— which often required skilled machinists to numerically program step-by-step toolpaths. Today’s technologies allow for rapid precision machining and more agile factory setups; manufacturers can digitally upload a new design to an entire factory or network of many interconnected factories, rather than re-tool every single machine whenever they switch products. Two notable consumer trends⁶ also support a push toward smaller-batch production: the desire for personalization and customer engagement, and rapidly-changing, regional fashions leading to faster product turnover.

What is the overall effect that the increased ease and affordability of flexible, small-volume production will have upon the traditional manufacturing paradigm, which is currently dominated by high-volume manufacturing and large-scale factories— but also contains a mix of both independent and vertically-integrated SMMs?

Key questions for the future include the following, which will be discussed in the following sections:

- A. Who owns what?
- B. What’s the scale of production?
- C. Where does manufacturing happen?
- D. How do SMMs interact?

A. Who owns what?

Maker idealists would advocate for the tenuous promise of “democratizing manufacturing,” categorized here as the “Fab City” model of predominantly local production of locally-designed goods for local consumption.⁷ Spearheaded by Fab Lab Barcelona, the Fab City initiative aims to “rescal[e] global manufacturing” such that the vast majority of products can be manufactured and then recycled locally: “A city’s imports and exports would mostly be found in the form of data (information, knowledge, design, code).”⁸ How does this differ from today’s local SMMs, and how would this affect ownership models?⁹ The Fab City idealist takes SMM fabrication to the

⁶ John Hagel, John Seely Brown and Duleesha Kulasoorya, “A movement in the making,” Deloitte Center for the Edge, <http://dupress.com/>, (January 24, 2014).

⁷ Throughout this paper, we assume that local SMMs provide a net benefit to communities and policy-makers ought to encourage their development.

⁸ Tomas Diez, “Fab City White Paper,” <http://fab.city/whitepaper.pdf> , (2016).

⁹ Although the USA is more prone towards mega-factories, some countries—notably Germany and Japan—already have a robust and competitive ecosystem of SMMs that produce highly-specialized and precise components or tooling equipment, often for larger companies. Electronics companies operating in

next level; instead of merely making components and specialized tooling (as most SMMs do today), Fab City SMMs would compete with large-scale factories and locally manufacture the bulk of their products themselves.

It is unclear to what extent the Fab City model can scale up in today's world of global monopolies and mega-factories. A Fab City full of SMMs attempting to make all products locally will have difficulty remaining globally competitive, especially given the Chinese government's recent pledge to subsidize automation throughout China¹⁰; highly-automated, high-volume manufacturing is practically guaranteed to yield the lowest possible costs—albeit with minimal local employment. Nonetheless, local competitiveness may change if policy-makers take action to favor local and/or non-automated industry over free trade, perhaps with the justification of supporting local jobs. Consumers who can afford the higher prices may also choose local brands over multinationals—just as the locally-grown food movement gained popularity across wealthier segments of North America and Europe. Local products may even be higher-quality and/or more relevant to local tastes.

Given that the ultimate goal is to support local economies (and not merely to resist foreign/non-local ownership), Fab Cities may find it beneficial to establish partnerships outside local industry, in order to scale up operations and benefit from the expertise of larger corporations. Local SMMs could perhaps partner with multinationals, or larger companies could even construct franchise, networked SMMs in the style of McDonalds that change their offerings to accommodate regional preferences.

Modern technological developments suggest three possible ownership models for a world of large-volume, small-batch production—in which each poses a different vision in relation to the global economy:

1. Fab Cities: a massive resurgence of small-batch, locally-created and locally-controlled production at a citywide level. This could involve wholly independent microfactories and/or local partnerships with larger firms.
2. Vertically-Integrated SMMs: an increase in local production capabilities that are integrated into large, networked systems.
3. Business as usual: large factories continue to dominate production, although some companies may adopt small-batch manufacturing techniques in house. SMMs and artisanal workshops carve out their own local market niches (customized products, repair parts, handicrafts, etc), but these don't drastically shift the high-volume manufacturing paradigm.

We anticipate some growth in Fab Cities and Vertically-Integrated SMMs, as well as

Shenzhen, China also employ local subcontractors to fabricate certain components—which feed into a self-reinforcing loop of more successful electronics companies fostering an even stronger ecosystem of well-connected SMMs.

¹⁰ Ben Bland, "China's robot revolution," *FT Magazine*, www.ft.com, (June 6, 2016).

considerable overlap between these two models as municipal policy-makers prioritize creating local manufacturing capabilities over ensuring purely local ownership. Nonetheless, in the absence of extreme protectionist policies and/or disruptions to the global supply chain, we expect large-volume, globalized factories to continue dominating the manufacturing market.

B. What's the scale of production?

The skeptic would highlight a key fact that is often missing from discussions around 3D printing and related technologies: *small-batch production does not necessarily correlate with localization*. For any given manufactured product, we find it useful to separate the size of a factory (say, a neighborhood microfactory vs. a traditional high-volume production facility like Foxconn) from its production volume (small batches of 10s-1000s vs. large batches of 100,000s-millions).

Considering the costs and radically different logistics inherent to redistributed manufacturing, skeptical realists argue that companies could just as easily employ their own agile and small-batch manufacturing tools in giant factories or factory-clusters—which, depending on the product and relevant government policies, may be more profitable than a Fab City or Vertically-Integrated SMM model. Instead of local customization, companies could provide tailored products through centralized 3D printer clusters, which can then be shipped worldwide to consumers. Even though design and manufacturing can theoretically be based anywhere, companies may find it more profitable and/or easier to continue their traditional high-volume manufacturing models rather than shifting to a more distributed paradigm.¹¹

¹¹ Several examples lend credence to the skeptic's argument. New Balance recently launched an experimental, small-batch run (44 shoes) of their new 3D printed running shoe—which were fabricated in one batch in their existing, traditional high-volume manufacturing facility, instead of pursuing a more local production model (New Balance, "New Balance to sell first 3d printed running shoe," New Balance Press Box, <http://newbalance.newsmarket.com>, April 11, 2016).

Consider also the case of GE's new mega-factory in Maharashtra, India: an agile factory employing modern digital fabrication technologies, allowing the company to rapidly produce small batches of customized products. Although the tools themselves would be equally productive if spread across a network of micro-factories, GE has decades of expertise and sunk-costs in high-volume production and complex supply chains; they had no particular incentive to decentralize their manufacturing and pursue an entirely new production model (Maxx Chatsko, "General Electric Company Wants You to Meet the Factory of the Future," The Motley Fool, www.fool.com, March 28, 2015).

Even if redistributed production were definitively proven to be cost-effective for large companies (a highly indeterminate "if"), the experience of Cardiff University researchers Dr. Paul Nieuwenhuis and Dr. Peter Wells reveal that large-scale manufacturers wouldn't necessarily disrupt their global supply chains. Nieuwenhuis and Wells have argued for decades that local assembly and retail facilities would be more cost-effective than shipping pre-assembled cars (i.e., empty metal boxes) worldwide while paying for retail locations—and yet only new vehicle start-ups have expressed an interest in testing out this model. Perhaps established automotive companies are unwilling to shift their current model of production, even if they can be convinced of the long-term benefits to a redistributed model (personal conversation with Paul Nieuwenhuis, April 2015).

Independent of redistributing manufacturing, one key benefit to the idea of full-product, small-batch production is the flexibility it affords companies to rapidly iterate and test out new products—without exorbitant retooling costs or the necessity of economies of scale. Low-volume, manufacture-on-demand could become an alternative to stocking large inventory, especially if smaller production runs become the norm. For example, global manufacturing logistics company Flex supports a small-batch microfactory (using digital fabrication techniques) for both customized production and testing new hardware ideas, as described by UC Berkeley professor Dr. John Zysman:

Here very low volume is undertaken with fully industrialized production, both industrial equipment and supply change arrangements. The Flex Invention Lab permits production and process revision but the industrial standards mean the process is ready to be moved to volume. The initial per unit cost can be 2X-10X but in small batches the price differential with fully constituted volume manufacturing is unimportant. As these manufacturing processes for particular products become more standardized, Flex and its clients can consider moving the production system to a middle volume production location, often still in an advanced country. Then as demand – hopefully – spikes, the production system may again be transferred, this time to a very high volume location... Flex's announcement of growing ties to the Tech Shops that are rooted in the 'maker movement' suggests that, rather than centralized factories or decentralized individual customization, entirely new approaches to production organization, and with it new strategies for entrepreneurship and new requirements for skill, may emerge.¹²

Flex's variety of microfactory is likely to remain localized within particularly innovative communities, for the convenience of nearby inventors and entrepreneurs.¹³ While Flex's success could have a substantial impact upon production organization and hardware entrepreneurship, it will have a negligible effect on the traditional large-volume manufacturing paradigm. When demand increases for successful Flex products, inventors have little incentive to continue with costly, small-batch manufacture. They will likely scale up through a more traditional route, with additional support from Flex—a company that, incidentally, makes the bulk of its corporate profits through traditional high-volume manufacturing.

C. Where does production happen?

¹² John Zysman and Martin Kenny, *The Next Phase in the Digital Revolution: Platforms; Abundant Computing; Growth and Employment*, Berkeley Roundtable on the International Economy, unpublished paper draft, (August 6, 2016).

¹³ As another example, GE Appliance's FirstBuild Microfactory in Louisville, Kentucky is a small-batch test bed for home appliances. GE Appliances can then rapidly iterate and manufacture any viable products, in partnership with the inventors (<https://firstbuild.com/microfactory>).

We identify two cost elements that play into a company’s decision of where to locate their production: the pure economic cost (as determined by shipping costs, location, infrastructure, wages, etc) and the politically adjusted cost (accounting for trade policies and import taxes). Protectionist policies would clearly favor more local production— following the model of the Fab City or Vertically-Integrated SMMs— whereas an increase in free trade would likely strengthen our current globalized system. As we’ve said before, answers to all these questions of location will likely depend more upon policy decisions and transportation costs than technological advancements.

Starting with the pure economic costs, which products (or components of products) are best produced at large-volume, and which have greater potential for small-batch local manufacturing? Also, which aspects of production make the most sense to localize? Perhaps SMMs would find it most profitable to merely assemble fully-manufactured components at a local scale, providing only a slight modification to current large-volume production ecosystems and global supply chains.

Large-volume manufacturers have developed robust and scalable production methods for many product components— such as small, complex electronics like microprocessor chips and LEDs, which would be highly expensive (and perhaps physically impossible) to create from scratch. Although most circuitry components will likely continue to be mass-produced, new desktop-sized pick-and-place machines do enable modern SMMs to produce small batches of circuit boards (though not constituent components) both locally and affordably.

In the case of plastics, the small-batch 3D printing company Type A Machines (a manufacturing contractor and 3D printer manufacturer in California) found that 3D printed plastic components can be cost-competitive with injection molding out to 10,000 units— when 3D printing relatively small components, and using 20 “reliable, networked managed” desktop 3D printers operating in parallel with appropriate downtime.¹⁴ (Metal 3D printing is likely to become somewhat more affordable, although it will still be limited by the inherent physical difficulties and high temperatures required.) Ironically, Type A Machines is pursuing the mega-factory model of hundreds of 3D printers operating in parallel in the California Bay Area—rather than spreading out production across local workshops. In contrast, the online platform startup Fictiv matches designers to local SMMs with 3D printers and other digital fabrication tools— and they aim to support a network of micro-factories, which could each contain a few dozen 3D printers to compete with Type A Machines on a more local scale. Fab City supporters would prefer Fictiv’s more independent model of SMMs, even though the platform itself might (like Uber) be foreign-owned.

For somewhat larger volumes of plastic parts, SMMs could purchase or rent time on a

¹⁴ A. Rutter and V. Sharma, “Low volume, agile, additive manufacturing and capital costs,” www.typeamachines.com, (Type A Machines: November 2014).

small-scale injection-molding machines and mill their own molds. The Flex microfactory mentioned above even uses 3D printed plastic molds for small-batch injection molding, to cut costs and save many hours per mold.

Maker idealists cite increased difficulties for global supply chains as a predictor for localization— perhaps due to the unpredictable effects of global warming or the potential for rising fuel costs.¹⁵ A disruption in global supply chains could indeed lead to increased local production, especially for large household appliances and vehicles that cannot be easily flat-packed into shipping containers. While most vehicle components do require manufacturing economies of scale, production aspects such as assembly, auto-body fabrication, and painting could easily occur locally. As described by Dr. Peter Wells and Dr. Renato Orsato, the redistributed manufacturing model of “Micro-Factory Retailing” (MFR) could minimize shipping costs and logistics, while enabling vehicle companies to reduce their perpetual problem of over-supply and save considerably on external retail partnerships:

For example, rather than having one large plant producing 250,000 cars per annum (an average break-even point in traditional car manufacturing) the MFR approach would involve 50 plants, each assembling 5,000 cars per annum (i.e. 250,000 in total) and distributed spatially to match concentrations in population... There would be no separate distribution channels or sales outlets: the factory is also the sales, maintenance, service and repair location. Powertrain components and other generic items could be centrally produced in conveniently located highly automated facilities for distribution to the decentralised assembly plants, thus allowing small scale assemblers to benefit from externalised economies of scale.¹⁶

While the Maker idealist might extend the benefits of such microfactories to other steel-bodied household appliances such as ovens and washing machines/driers, the skeptic would raise concerns around brand diversity. If some micro-manufacturer only produces 5,000 cars per year, they have a limited opportunity to diversify their offerings on a regional level. Would such small volumes make sense economically? For particularly rural locales, is there enough demand to merit even the small-volume production that would make a local SMM efficient?

¹⁵ Richard Gledhill, Dan Hamza-Goodacre, and Lit Ping Low, “Business-not-as-usual: Tackling the impact of climate change on supply chain risk,” *Resilience: A journal of strategy and risk*, www.pwc.com/resilience, (PwC: 2013).

¹⁶ Peter Wells and Renato J. Orsato, “The Ecological Modernisation of the Automotive Industry” in: Klaus Jacob, Manfred Binder and Anna Wieczorek (eds.), *Governance for Industrial Transformation, Proceedings of the 2003 Berlin Conference on the Human Dimensions of Global Environmental Change*, Environmental Policy Research Centre: Berlin, pp. 373 – 385, (2004).

One must also consider the politically adjusted cost of production: will policy-makers be incentivized to foster localized, small-batch manufacturing? Redistributed manufacturing loses out on economies and policies of scale— SMMs often lack reliable supply chains and skilled worker pools, and cost considerably more. Maker idealists pose three local benefits that might mitigate these costs: redistribution helps the environment by minimizing unwanted product and facilitating recycling, it helps society through better local employment opportunities, and it helps local companies retain their competitive edge through rapidly-deployable innovation.¹⁷ From an overall environmental standpoint, it remains to be determined whether localized companies are indeed more sustainable.¹⁸

In addition to economic considerations, the ability to locally manufacture products on-demand can significantly decrease turnaround time for customized items. Amazon’s CreateSpace division, for example, provides on-demand book-printing services through their contractors in several states across the USA, to help publishers “realize all the benefits of physical book sales without any up-front investment, returns, or inventory risk.”¹⁹ This model may merit further investigation, especially if consumers’ demand for same-day delivery increases and the rapid shipping costs become more than the additional costs of on-demand production.

D. A production system for Small and Medium Manufacturers?

There has been considerable academic discussion around Global Production Networks—initially from a pre-digital perspective, and more recently addressing the concept of cyber-physical systems. The rise of the platform economy has led to well-connected, geographically-distributed networks, and micro-factories may well become an integral part of this newly cyber-physical world. We discuss a potential model for how SMMs might connect to the Internet of Everything, and pose several open-ended questions on the topic.

¹⁷ Erwin Rauch, Patrick Dallasega, and Dominik T. Matt, “Sustainable production in emerging markets through Distributed Manufacturing Systems,” *Journal of Cleaner Production* 135 pg 127-138, (2016).

¹⁸ The optimized production lines and processes behind mass manufacturing are many times more energy-efficient than dozens of local shops creating their own products. Even the carbon emissions that come from shipping products around the world might not make up for the waste created by inefficient local manufacturing. Furthermore, in many countries like the USA, toxicity regulations are deliberately relaxed for small businesses to minimize startup costs—which could potentially lead to improper disposal and unwitting environmental devastation. Such regulation could yield disastrous results in Fab Cities, where all SMMs might be able to escape scrutiny due to their small size (personal communications with Terry Foecke, Head of Supplier Development at PCH International, December 2015). Italian researchers Rauch, Dallasegaa, and Matt maintain that a redistributed manufacturing model would be more socially and environmentally sustainable; they call upon policy-makers to strengthen local SMM networks in emerging economies as part of the effort to reduce global warming. They focus especially on the food processing industry, which requires timely, local production to keep produce from spoiling— and final products often vary regionally depending on local preferences (Rauch, Dallasega, and Matt, 2016).

¹⁹ CreateSpace, “Services Available for Publishers,” www.createspace.com, 2016.

Advanced matching algorithms, such as those employed in UberPool to facilitate carpooling, could assist companies in finding distributed manufacturers and transporting their goods more efficiently. If manufacturing companies decide not to build their own local micro-factories, they might acquire existing SMMs or pivot towards a service model and contract out their manufacturing following the Vertically-Integrated SMM model. MIT's *Production in the Innovation Economy* offers the following description of a cyber-physical manufacturing network:

In a world of fragmented production, when a company needs a part, it does not build a factory. Rather, it taps into a national network portal and places a computer-aided design (CAD) description of the part it desires, and the numbers it needs, on the portal. To protect its intellectual property, it may perhaps modify the part somewhat. Meanwhile, software systems from small manufacturers around the country prowl the portal looking for parts to bid on. Each manufacturer has a rating, not unlike the system used by eBay, and provides a capacity and response time. Small manufacturers can produce only small numbers of parts, so many small companies might be necessary to meet the customer's total needs... In this massively distributed, massively parallel way, parts are rapidly manufactured around the country.²⁰

This ensemble of on-demand SMMs would employ the latest in sensor technologies and the Internet of Everything (IoT or IoE) to simplify factory operations, track components, and facilitate quality control and assurance. Quality control could be done on site at the micro-factory, at some designated location en route to the final destination, or at the headquarters of the company that originally ordered the part.

Despite the advent of new technologies, it will still be difficult to implement a robust quality control system across a continually-shifting group of distributed SMM suppliers. Variances across different, geographically-distributed factories will require substantial effort to mitigate, especially if all the products from various regions must meet the same quality standards and tolerances. Former TechShop CEO Mark Hatch notes that he ran into quality problems when manufacturing small batches of the same product in various Kinko's offices across the USA— even though his team controlled the entire environment.

Ideally, a world of SMMs would also be “smart”²¹ enough to minimize transportation by manufacturing and/or assembling products close to the final consumers. “Smart” SMMs

²⁰ Suzanne Berger, MIT Task Force on Production in the Innovation Economy, *Making in America: From Innovation to Market*, (Cambridge, MIT Press: 2013), pg165.

²¹ “Smart” as in smartphone— not necessarily artificially intelligent

could join forces to create a cohesively interconnected manufacturing infrastructure at a regional level—which perhaps could lead to more collaborative relationships among SMMs, just as utilities have no incentive to compete with companies outside their jurisdiction. Enhanced regional networks might allow companies and start-ups to test out small batches of new products in various geographical regions before scaling up production, as an extension of Flex’s local microfactory model.

If “smart” SMMs manage to turn metropolitan and rural areas alike into Fab Cities, how would this trend of globally-redistributed manufacturing evolve over time? How might these shifts affect local jobs, and what role would automation play in the entire ecosystem? Furthermore, how would SMM networks differ from regions that already contain thriving ecosystems of SMMs (such as Germany or Japan) to regions dominated by multinationals (such as the USA) to emerging markets with minimal advanced manufacturing infrastructure?

Nonetheless, the skeptic would point out that Germany’s national plan for “smart” manufacturing has very little to say about redistribution. Germany’s *Industrie 4.0* is an explicitly corporatist strategy for a cyber-based, industrial future, presenting a vision in which networking capabilities, sensor-based knowledge and control, and agile factory equipment will bolster SMMs and affect production. While *Industrie 4.0* does forecast the decentralization of decision-making and the creation of more autonomous systems, its overall ownership model of SMMs is ill defined. [CITE white paper] *Industrie 4.0* could be equally suited to component manufacture by independent SMMs (the status quo in Germany), or a Vertically-Integrated SMM model for multinationals. The skeptic may even envision a world of *Industrie 4.0*-equipped, small-batch production facilities within existing mega-factories—in which SMMs remain a niche market in a world dominated by high-volume manufacturing and the occasional one-off, personalized product.

2. Personalized Production: Realistic Trekkies

We next move to the concept of hyper-local fabrication, on the personal and/or artisanal scale of one-off production.

The skeptical realists might be put off by the popular Trekkie idealist’s argument, which gives the entire Maker-Industrial conversation a bad name. Let us clarify the Trekkie position, since it is part of the discussion, and then move beyond to more practical considerations. As the most extreme of Maker idealists, Trekkies foresee an entire world of fabrication on the personal scale; like the *Star Trek* replicator or the matter compilers of Neil Stephenson’s *Diamond Age*, every community could have access to an advanced fabrication device that allows anyone to make anything at any time. Given the fledgling state of modern nanotechnology, we believe that this view is better suited to basic research and science fiction than our current paper—at least for the time being.

Trekkies may cite the expansion of personalized goods, especially given the ease of

creation afforded by the Maker Movement and modern digital fabrication tools. Though aspects of their model are technologically feasible, impossible volumes of one-off products would be necessary to compete with high-volume production— and such artisanal products are generally higher-cost and target a wealthier population segment.²² In addition, large-scale personalized production would require a significant number of people to contribute substantial time and effort, and the average unskilled citizen has little incentive to produce his or her own products—assembling Ikea furniture is complicated enough.²³ Absent some unprecedented breakthrough in nanotechnology, a radical cultural shift away from mass-consumerism, or an economic/geopolitical catastrophe that forces local production, we take a skeptical view: there is little evidence that personalized or artisanal production will experience significant enough growth to substantially disrupt the entire high-volume manufacturing market. In other words, successful craft businesses serve a fundamentally different market niche from high volume production.

There is also an artisanal version of the Trekkie vision— which may impact specific niche markets, but is unlikely to form the foundation of a brand new production system. We identify three ideal candidates for just-in-time, one-off production on a large scale: products sold as “experiences,” personalized medical devices, and products needed in disaster zones.

First, on-demand digital fabrication allows retail companies to sell products as interactive experiences rather than merely consumable goods—from the companies that will 3D-scan your body to make customized action figures, to Build-a-Bear’s DIY teddy bear parties, to labor-intensive artisanal products that come with their own stories of creation. Mark Hatch states that “experiences are eating manufacturing and service offerings,”²⁴ implying that customers are already shifting from mass-market consumerism to more

²² Online artisanal marketplaces such as Etsy.com support 1.6 million active sellers (many of whom employ new fabrication technologies), and roughly 30% consider their crafts their main businesses (Etsy, *About Etsy*, www.etsy.com/about, 2016). Yet only 5% of Etsy sellers have paid help, and 95% operate their businesses from home (Etsy, “Building an Etsy Economy: The New Face of Creative Entrepreneurship,” <http://extfiles.etsy.com>, 2015). Unless there is some major market shift, most of these small businesses will continue to provide minimal job opportunities, and those that do scale up will likely follow a traditional route towards high-volume manufacture. Etsy’s own initiative to help artisanal businesses scale up seems to involve partnerships with existing high-volume manufacturing brands rather than any support for new local microfactories.

²³ To take one example of the impossibility of this Trekkie notion of the future, consider how the media has enthusiastically over-hyped desktop 3D printers for the creation of everything from toys to jewelry to firearms. Most desktop 3D printers are mass-produced in a traditional fashion, and may come with their own proprietary, mass-produced feedstock—like Hasbro’s decades-old Easy-Bake Oven. These toy ovens made it easier and safer for anyone to create customized baked goods, but sales of the Easy-Bake Oven were unlikely to correlate with decreased demand in sales of packaged cookies. Thus, Hasbro’s simplified oven fundamentally remained a toy rather than a competitor for local baked goods production—it did not “democratize” baking in ways that substantially impacted the market. Desktop 3D printers, similarly, are more of a novelty item than a significant threat to the American high-volume manufacturing paradigm.

²⁴ Personal communication with Mark Hatch, (October 2016).

emotionally-significant products. Nonetheless, an analysis of consumer purchasing trends may be necessary to assess whether this shift is actually occurring or whether it's mostly hype around new technology.

Our second category for this sort of production is medical devices. Patients with special needs may require immediate, very specific customizations to generic devices that don't need to be robust or long-lasting—and 3D printers, easy-to-program microprocessors and sensors, and other low-cost Maker tools can provide these capabilities. Dentists have employed external 3D printing firms to create customized crowns (to cap tooth implants) and “clear braces” like Invisalign for over a decade—mostly in a high-volume manufacturing setting. Now that digital fabrication has become more affordable and ubiquitous, some high-end dentists have started making crowns for their patients in-house, leading to much faster turn-around times and perhaps lower costs. Customized eyeglass manufacture is another highly personalized application, which has already gained some popularity for both high-end markets and cost-conscious customers in remote areas of emerging markets. In hospitals across the USA, MakerHealth is launching a network of makerspaces to “enable nurses, doctors, and patients to work together on the floor unit in a unique medical fabrication environment with everything they need to create their solutions.”²⁵ Through this program, nurses have come up with a number of devices that they can immediately implement into their hospital routine, including foot-powered inhalers for amputees and custom training tools for hospital staff.

Finally, local fabrication may make sense in disaster zones where logistics and shipping alone can cost aid organizations up to US\$15 billion per year, and the higher cost of local production thus becomes irrelevant.²⁶ Several aid organizations—notably Communitere, Field Ready, and the UN and ICRC's Global Humanitarian Labs—are bringing 3D printers and other technologies into disaster zones and refugee camps to locally fabricate medical tools, replacement parts for vehicles, and potentially farming equipment. However, we may need a few more years before digital fabrication tools can substantially disrupt logistics for humanitarian aid; most of today's desktop 3D printers are somewhat fragile and can only print with a limited set of plastic materials.

Although both of these personalized manufacturing niches may have the potential to revolutionize their respective fields, we foresee a negligible overall impact upon our globalized, large-volume manufacturing paradigm.

3. After-market repair and customization

Instead of posing an entirely new manufacturing paradigm, the third Maker-Industrial

²⁵ MakerHealth, “About MakerHealth,” www.makerhealth.co, (2016).

²⁶ Centre for Research on the Epidemiology of Disasters, CRED Crunch: Disaster Data, Issue No. 35, (April 2014).

argument focuses on the potential for local repair and/or customization after the sale of some product. Although repair is quite different from customization in practice, we combine the two aspects here in order to discuss local after-market servicing and product modularity.

Local micro-factories could produce on-demand repair parts for a variety of products, although more complex components (electronics, engines, etc.) might still be produced through large-scale traditional manufacturing and then shipped into repair-shops from abroad. Given the relatively low cost required to make one-off products with modern digital fabrication tools, repair-shops could also provide local customization services as needed.²⁷ Idealists argue that the Maker Movement could lead to the expansion (and perhaps formalization) of local customization/repair-shops worldwide, and significantly impact our current model of product consumption—while creating new job opportunities for micro-enterprises.

The skeptic would point out that, just as small-batch production can just as easily happen in a large factory, several major corporations are developing a centralized model for repair (and possibly customization) in the vein of today's high-volume manufacturing paradigm. Earth-moving equipment manufacturer Komatsu, for example, has expressed interest in providing customers with a sort of lifelong lease for their tractors, rather than the typical transfer of ownership that would otherwise occur. This perpetual-lease model may be advantageous in a world of resource shortages and price volatility, particularly for larger products; it allows the central company to know exactly which resources are in the company's possession across all of its wares worldwide, since most products will be returned to the company upon termination of the lease and/or the product lifecycle. Komatsu would thus have an incentive to make a more repairable tractor, though not necessarily a more open one—customers may have to ship any broken components back to Komatsu headquarters for repair or replacement. Unless such companies identify significant benefits in licensing their hardware, repairs and modification in this perpetual-lease model may be restricted to a small number of company-authorized technicians.

As the Internet of Everything gains steam and computer chips start appearing in all manner of internal components, unlicensed repairs on closed technologies may become dangerous and costly, especially for companies that prefer to lease rather than sell their product. While Komatsu does not mandate that their renter-customers use authorized technicians, the company will buy used tractors back for a higher value if they determine that they were well maintained.²⁸

²⁷ This model is already well known across emerging markets, where the lack of reliable supply chains has led to many “informal sector” repair/customization shops. The unsanctioned hacks of informal repairmen are often brilliant and hazardous in equal measure—such as elongating truck beds, re-boring vehicle engines to use differently-sized cylinders, and building tractors using inefficient water pump engines.

²⁸ See Appendix 2 to contrast Komatsu's model with two Open Source Hardware (OSH) tractor startups on the one hand, and John Deere's attempt to forbid unlicensed modifications/repairs on the other hand.

To create more repairable/modifiable products, companies may need to go back to the drawing board and redesign entire components from scratch. Might companies have an incentive to create more standardized, interchangeable hardware components—especially those that could be combined across different manufacturers? Shared libraries and compatible standards will play a key role in the success or failure of this idea, as we discuss in the next section. Unfortunately, complex and modular products have not yet met with much success outside the Maker community—yet they do exemplify a new model for repairable products in a networked world. Eschewing the predominant consumer electronics model of planned obsolescence, several smartphone manufacturers have created phones that can be updated in a modular fashion as technology improves. Nonetheless, idealists shouldn't get too excited about this model yet: modularity, like reparability, is not by itself a predictor of localization. If products are too easy to repair or modify, customers will have no need for repair-shops and could perhaps purchase all components directly from Shenzhen or wherever.²⁹

While policies against planned obsolescence could have a moderate environmental impact³⁰, contentious policy-makers may find a compelling rationale to support local repair in the prospect of job-creation. As manufacturing process becomes increasingly automated, repair and customization will remain complex and variable tasks that likely require human intervention. The Fab City model might feature local repair-shops to employ qualified technicians in every neighborhood (perhaps a more organized network of today's Repair Cafes), equipped with all the tools required to make their own parts for many different broken or outdated products. These workshops may have some spare parts in stock, or even base modules that can be turned into a variety of different components. A viable network of repair-shops would also facilitate local customization, especially for Open Source products (or even partially-open products) that encourage user modification by "prosumers" (proactive consumers). This could lead to a positive feedback loop like the app stores for Apple and Android, in which increasing numbers of

²⁹ In a *Wired* review of the first fully open-source, conflict mineral-free, readily-repairable, and modular smartphone Fairphone 2, the reviewer concludes, "Overall, the Fairphone 2 is a decent phone with an exciting internal design and a boring exterior design. With a price tag of 529 euro (\$590) it is quite expensive, especially considering how much mid-range Android phones have improved lately, offering high-end specs at much cheaper prices" (Maurizio Pesce, "Review: Fairphone 2," *Wired*, <http://www.wired.com>, February 11, 2016). Since the Fairphone features modular and interchangeable components, the team hopes to attract an ecosystem of developers to collaboratively improve their product. The key question, however, is whether consumer electronics can fundamentally be profitable if they don't attempt the Apple model of temporary monopolies on innovation—and instead pursue an open-source alternative. Fairphone's components are mass-manufactured, if not always mass-assembled.

³⁰ When considering environmental concerns, one needs to ask whether an ecosystem of spare/alternative parts would lead to less waste or rather increased consumption, as users take advantage of the customizability of every component. Google's Project Ara website boasts about how their modular (and mass-manufactured) smartphone "allow[s] for upgrades, innovation and style"—does this mean that, instead of purchasing upgrades only when necessary, consumers will collect a plethora of different cameras or cases or motherboards to "Mix. Match. Swap." whenever they like? (Google ATAP, "Meet Ara, the modular phone," <https://atap.google.com>, 2016).

designers and companies create add-ons for modular products and thus make OSH products more attractive and affordable than less open alternatives.

While there is much more that needs to be investigated before we create a viable repair economy, repair and customization still hold great promise for a Maker-Industrial Revolution.³¹ Local SMMs would greatly benefit from a corporate ecosystem of generic, interoperable parts that could fit different product models. Micro-factories could incorporate repair services along with assembly, retail, and perhaps customization—all in the same local, agile workshops.

II. Issues Emerging from Maker Debates

Whatever the ultimate outcome, the move toward redistributed production/repair and the notable increase in personalized manufacturing force two sets of issues: current intellectual property rules will be strained, and the implications for emerging markets bear consideration.

1. *What happens to IP?*

The digitalization of production will have interesting implications for our antiquated IP model. Certain Maker idealists even advocate for a world of entirely Open Source Hardware (OSH) IP— and we will address their vision in the last sub-section.

A. Challenges to our current IP model

IP legislation will certainly require some revision as manufacturing becomes increasingly digital; as bits and atoms become more interchangeable, ideas become easier to steal. 3D X-ray scanners already exist and are rapidly lowering in price; anyone could theoretically digitize and re-create a patented product such as an iPhone, although the one-off production costs would be exorbitant. Less complex products may have more to fear from X-ray scanners, especially those that rely upon clever but simple IP. In the USA, we face a return of the controversial DMCA laws that resulted in arrests of children and the elderly for pirating media. What happens to IP, copyright, and informal trade secrets under the Vertically-Integrated model if dozens of independent SMMs and outsourced designers (rather than in-house or dedicated contract

³¹ There will also be niche cases in which the ability to create repair parts is particularly beneficial. Customization of components in remote areas could provide a significant advantage, especially given the typically volatile conditions of war and natural disasters. US marines used digital fabrication tools to build a one-off replacement part for a tank while stationed abroad. This took them only one day— rather than the 1000 days typically generally required to request, manufacture, and ship a replacement part into the field (presentation by Kristin Holzworth, director of the Joint Advanced Manufacturing Region Southwest at the USA Department of Defense, June 2016).

manufacturers/designers) are employed to create a single product?

As it becomes easier to bring new ideas to market, we will also need to beware of “patent trolls” who buy up vague patents and then hire teams of lawyers to sue companies who— generally unintentionally—have used those ideas in their products. Overzealous enforcement of patents and copyrights may hinder new product development in small firms throughout the USA, even as robust IP protections help the country maintain its global lead in innovation.³²

In our increasingly digital world, it may make sense for policy-makers to encourage more openness—and perhaps even Open Source Hardware— in an effort to foster innovation.³³ The question is, would a more open approach substantially increase innovation and minimize attempts to reinvent the wheel (while still allowing companies to benefit from hard-earned trade secrets)?

B. Introducing Libraries and Standards

Without commercially viable, interoperable digital standards for manufacturing, the Maker-Industrial world may never come to fruition. Companies should be able to digitally outsource their design process and/or license existing ideas, without struggling over compatibility issues and unnecessarily restricting access to trade secrets. In the Fab City model, independent SMMs must rise to the challenge of full-product manufacture— and thus will need access to detailed product information that’s compatible with their various machines. Unlike high-end artisanal producers, successful

³² Bessen et al (2015) estimate that patent legislation in the USA costs businesses tens of billions of dollars every year, and IP lawsuits regularly bankrupt very small businesses— while forcing firms to curtail “innovation and new product introduction.” (James Bessen, Peter Neuhäusler, John Turner, and Jonathan Williams, “Trends in Private Patent Costs and Rents for Publicly-Traded United States Firms,” Boston Univ. School of Law, Public Law Research Paper No. 13-24; Boston Univ. School of Law, Law and Economics Research Paper No. 13-24, <http://ssrn.com/abstract=2278255>, March 2015).

³³ In contrast to the USA’s unnecessarily strict IP regime, the Chinese manufacturing ecosystem employs an intriguing combination of loose patent enforcement and illegally-shared designs, enabling Chinese entrepreneurs to cheaply and rapidly innovate without fear of copyright infringement. This informal model also encourages companies to create more interoperable components. Inventor and manufacturer Bunnie Huang coins the term “gongkai” or “open to the public” to describe this phenomenon (Bunnie Huang, [“From Gongkai to Open Source,” www.bunniestudios.com, December 2014](http://www.bunniestudios.com)):

Gongkai is more a reference to the fact that copyrighted documents, sometimes labeled “confidential” and “proprietary”, are made known to the public and shared overtly, but not necessarily according to the letter of the law. However, this copying isn’t a one-way flow of value, as it would be in the case of copied movies or music. Rather, these documents are the knowledge base needed to build a phone using the copyright owner’s chips, and as such, this sharing of documents helps to promote the sales of their chips.

Grassroots artisans in emerging markets have their own variance of *gongkai*, for sharing ideas in repair, customization, and manufacturing. Perhaps the USA could learn from the thriving, open SMM ecosystems of China and emerging markets and loosen IP standards accordingly—otherwise, small USA companies may be too afraid to pursue new hardware ideas without joining forces with larger corporations.

SMMs that compete on the mass-market probably won't have the extensive bandwidth and budget required to design their products from scratch.

A unified, interoperable library of product designs may thus be crucial to the success of redistributed production and repair. Designers and/or their respective companies could upload CAD files for download and perhaps modification, depending on the license. Library users may be able to choose between free designs, which are perhaps licensed under OSH, and paid designs, which may come with some quality guarantee depending on the brand.³⁴ Designers may be able to set various rental or ownership restrictions for their CAD files, just as the entertainment industry allows users to rent or download digital music and film. The platforms behind these libraries also bear further exploration: who will own these platforms? Will these be for-profit entities such as Google and Uber, or could some municipality or aid organization develop an equally viable platform for their own purposes? If there continue to be a plethora of different project-sharing platforms, will they all follow compatible standards for their CAD files or operate in silos? How could IP encourage or inhibit interoperability between different brands and various factories, and what sorts of standards will we need to create?

Consider the possibility of a new breed of freelance product designers and prototypers, with accompanying platforms of available designs-for-purchase. In a fully digitized manufacturing world, competent individuals can design products for remote companies and upload their digital models to project-sharing platforms such as Thingiverse.com (for sharing CAD models for 3D printing) for others to utilize.³⁵ Companies can license, download, and manufacture popular models rather than designing their own products from scratch. Hybrid strategies are also possible, where companies share generic designs for users to customize and “fork” to their own versions. Just as a handful of highly-successful “YouTubers” earn a living by generating videos with millions of views (out of at least a billion total YouTube videos), highly-skilled and freelance product designers may eventually be recognized and compensated for their talents.

One key setback is, as Makers like to say, the fact that “hardware is hard.” Electromechanical devices diverse, variable, and complex; there is no effective, widely adopted platform to share hardware designs in the way that software developers share their code (although a number of start-ups are competing for the position).³⁶ Until this

³⁴ Just as computer users can choose between paying for the high-quality Microsoft Office or freely downloading (and perhaps contributing to) the open source package OpenOffice, SMMs may be able to choose which product files to use depending on their budget and ideology.

³⁵ <http://www.thingiverse.com> is a subsidiary of MakerBot Industries, LLC. The Thingiverse platform currently features hundreds of thousands of unique products, with an average of just a few actual 3D prints per item—indicating personalized rather than redistributed production (personal communications with Thingiverse staff, June 2016).

³⁶ To quote Andreas Bastian, senior research scientist at Autodesk and volunteer in the distributed, OSH 3D printed prosthetics community e-NABLE (www.enablingthefuture.com): “something that is really holding back the entire Open Source Hardware community is that there are some deep, fundamental incompatibilities and systemic challenges to sharing 3D design.” 3D designers working across different

challenge is addressed—or some particular company dominates the CAD software market, which is increasingly unlikely—neither OSH designers nor SMMs will be able to easily modify and share product designs. Companies and policy-makers will likely need to introduce a more formal set of hardware and CAD standards. With diverse SMMs competing and collaborating on similar manufacturing jobs, hardware standards may become necessary to maintain quality control, to help companies communicate better with local SMMs, and to assist SMMs in easily operating their own digital fabrication equipment. Just as the early, US military-funded inventors of the Internet created a set of open and accessible protocols for all users to build upon, several private companies have joined the OSH community in attempting to create more compatible information highways for digital manufacturing.

Finally, modular design may become increasingly advantageous as distinctions blur between software and hardware, and more devices take on computer chips in order to join the Internet of Everything—as discussed in the previous section on After-Market Repair and Customization. Comprehensive design standards could incorporate manufacturing protocols, and could even be introduced at the initial design stage, perhaps leading to interchangeable, modular components to facilitate compatibility across competing brands and diverse micro-factory configurations.

C. Open Source Hardware

The Maker idealist would advocate for a new IP regime that champions Open Source Hardware (OSH). At the core of the Maker Movement is a fervent, often anti-capitalist belief in the benefits of sharing information and providing democratic access to both tools and designs, though open source models do not preclude inventors from profiting off their ideas. This may never be possible for certain top-secret products such as military hardware and new Apple devices, which may still need to be manufactured piecemeal—so only a single entity with proper security clearance can understand how everything fits together. Luckily for Makers, most consumer products (and even older versions of top-secret products) are unlikely to require this degree of secrecy.

Yet a main hurdle for OSH—and open modularity in general—is the fact that most consumer electronics are only highly profitable if, like Apple, they can continually be the first to market with some innovation (or at least something perceived to be a new idea). Unfortunately, this sort of innovation monopoly is a temporary status that only holds until another brand figures out how to copy your product—which leads Apple to pursue

platforms and applications often have to share files in the clumsy .STL format, which Bastian describes as “the difference between an image created in Adobe Illustrator with a lot of parametric control [the original file format], and an oil painting [the shareable but un-editable .STL file]... you can’t adjust the stroke weight in an oil painting” (Andreas Bastian, *DigiFabCon Keynote*, <https://vimeo.com/165786509>, April 2016). Despite being a closed source software company, Autodesk is adamant about developing Open Source tools such as the Spark network to facilitate 3D printing/additive manufacturing across diverse and even competitive platforms (<http://spark.autodesk.com/>).

fanatical levels of secrecy around IP and maintain as closed-source a system as possible. While Apple achieves high profits by catering to fashion-conscious early adopters, more open and affordable brands such as HP and Microsoft barely break even on their consumer electronics. Before major companies can embrace OSH, open source enthusiasts may have to provide a more serious capitalistic value proposition than the mediocre Fairphone mentioned earlier.

The concept of OSH bears a strong similarity to the Open Source Software (OSS) movement, which leads us to conclude that it's unlikely for OSH alone to revolutionize our current IP paradigm. While the OSS community has proved to be incredibly useful as a platform for corporate software, a unified standard for interoperability, and a tool to share ideas, the overall movement has not substantially shifted the dominant paradigm of software development and closed corporate IP. Nonetheless, one of the greatest successes of the OSS movement lies in its ability to prove that talented coders are willing to expend considerable effort towards a shared project for little or no monetary compensation; most OSH advocates would agree that this enthusiasm for sharing is equally true among hardware developers.³⁷ As demonstrated by Open Source communities, could there exist a viable IP alternative in which inventors can gain collaborators and recognition to improve their initial idea— ideally in addition to financial support? The entire concept behind our restrictive patent system is to encourage innovation, and experiences from OSS demonstrate that monetary compensation is not the only driving force behind new ideas. It's important to remember, however, hardware is much more difficult to share and standardize than code—given the wide range of possibilities for physical objects.

Many ideas from the Maker idealists could indeed prove valuable for constructing a new framework for hardware in the digital age—and yet these idealists get carried away into unrealistic visions of a post-industrial future, discounting current IP structures entirely in favor of a more perfect system that must be created from scratch. Perhaps OSH will, like OSS, solidify into a sizeable market niche. The OSH movement might also help tackle several issues with our archaic IP infrastructure—although new legislation could potentially solve these same problems without significantly increasing the degree of openness and sharing.

2. *What happens in emerging markets?*

If redistributed manufacturing gains popularity globally through networks of SMMs, could the shift toward localization and decentralization begin in emerging markets? What impact could this have upon development strategies? If the future will be full of Fab Cities with networked SMMs and digital rather than physical supply chains, why would emerging markets—which already suffer from costly and convoluted supply chain logistics— even bother with the outdated infrastructure of high-volume

³⁷ Steven Weber, *The Success of Open Source*, Harvard University Press, (Cambridge, MA: 2004).

manufacturing?³⁸ It remains to be determined whether local SMMs in emerging markets could solely provide goods for local customers, or if they could become the basis of a new export economy.

At the core of the Maker Movement in emerging markets is not merely a vision of redistributed manufacturing, but rather a radically local and anti-capitalist alternative to globalization.³⁹ While Fab City proponents in the USA might call for a rebirth of local production, an equivalent Fab City in Sub-Saharan Africa would likely introduce advanced manufacturing for the first time—and thus countries that currently import the vast majority of processed goods would become less dependent upon production in more developed countries. A completely self-sufficient Fab City model, however, is unlikely to happen in Sub-Saharan Africa; this would disrupt the neoliberal establishment on a global scale and invoke considerable backlash from multinational companies and governments across both developed and emerging markets.

Regardless of this fairly mercantilist goal, redistributed production/repair could still have a substantial development impact in emerging markets. We now discuss a more moderate, achievable vision.

We highly recommend that companies look into contracting out production to existing SMMs in emerging markets, and perhaps help to modernize the SMM sector in the process. Most of today's viable microfactory networks are already located in emerging markets—albeit in informal clusters that produce low-tech goods, through collaborative networks of skill-sharing and distributed repair/customization and production. Companies could also use high-volume production methods to fabricate equipment for SMMs, which would buy these tools to develop their own manufacturing enterprises and take advantage of locally-available feedstock.⁴⁰ This sell-the-tools-and-training model would especially benefit vehicle and appliance manufacturers—those who produce unwieldy products and might be attracted by local assembly to minimize their own logistics costs in hard-to-reach markets.

The lack of infrastructure and critical need for low-skilled jobs in emerging markets—combined with rising costs of logistics and carbon emissions—may even make redistributed manufacturing appear more attractive to emerging markets than developed nations. The question is, will the citizens of emerging markets—particularly in rural areas—necessarily have to choose between leading a modern lifestyle and

³⁸ Idealists may cite how rural telecommunications networks spread throughout Bangladesh long before cellphones became popular in rural North America and Europe. Just as Bangladesh “leapfrogged” the developed world by skipping landline telecommunications networks and jumping straight to mobile phones, some Makers foresee a similar trend for manufacturing.

³⁹ Dating back to economist EF Schumacher, anti-colonial freedom fighters such as Mahatma Gandhi and Kwame Nkrumah, and the backyard steel factories of Mao Zedong's China.

⁴⁰ Such as the Indian company *Saathi*, which sells an affordable device for making women's sanitary pads out of banana fibers.

fostering local self-sufficiency? Even though the model of local production for local consumption may not contribute substantially to GDP growth, the prospect of job creation, increased self-sufficiency, and enhanced stability may outweigh the costs. Increasing automation could replace up to 75% of jobs in emerging markets⁴¹, so perhaps a radically different development model would provide a better quality of life for the average citizen, regardless of international competitiveness.⁴²

Under some hybrid of the Fab City and Vertically-Integrated models for SMMs, micro-manufacturing networks could potentially become a staple of city-level infrastructure—like roads or electricity. One challenge for emerging markets will be to maintain enough local ownership over SMMs to benefit their own economies, rather than construct an entirely foreign infrastructure that only provides low-paying local jobs (such as the petrochemical industry in many countries). Many emerging nations have already established a precedent for Public-Private Partnerships and partial ownership models for other types of infrastructure, which could effectively support local development and job creation—especially when combined with policy regulations mandating that multinationals employ locals rather than foreigners.⁴³

While idealists can find much to fuel their optimism about SMMs for emerging markets, there is also cause for consternation. Advanced production facilities require local knowledge and training, as well as infrastructure, maintenance, and decent quality-control systems. Considering the severe lack of manufacturing expertise and the informality of current SMMs, how will emerging markets deal with quality control—both for final products and raw materials? On the side of human resources, will universities and vocational training programs in emerging markets adapt rapidly enough to provide the necessary knowledge and qualifications, and/or could local companies train their

⁴¹ Citigroup, “Technology at Work v2.0,” *Citi GPS: Global Perspectives & Solutions*, (January 2016).

⁴² In 1980, Ghana’s premiere technical university developed the Intermediate Technology Transfer Unit (ITTU) to provide both technology-based and knowledge-based support, and encourage a local shift from repair to manufacturing. Ghanaian and English engineers then created a network of 10 ITTUs promoting low-tech OSH across the country. These Units fostered hundreds of novel SMMs from metal casting to agricultural processing to beekeeping and related industries— through both training individuals and providing support for new business creation. There are no exact statistics available, but ITTU activities from 1980-1995 may have created tens of thousands (if not hundreds of thousands) of new jobs, and introduced hundreds of new industries to SMMs across Ghana. Although most of these SMMs might not be “networked” in the modern IoE definition, the ITTUs did introduce many individual products that are now manufactured in similar ways by diverse SMMs throughout the country. Since many of the owners of these SMMs know one another personally from ITTU workshops, they still gather together to share ideas for improving processes and products. The initiative clearly focused its efforts towards creating local jobs rather than pursuing economies of scale or national GDP growth—which may have led the more capitalistic Ghanaian government of the 1990s to stop providing significant support to the program. As automation eliminates jobs worldwide and Maker technologies provide more affordable options for SMMs, a new opportunity may emerge for programs that, in the vein of the ITTU or the Fab City concept, value local jobs and local value-creation over dramatic increases in GDP.

⁴³ Kenya’s leading telecom Safaricom is 40% owned by the Spanish company Vodafone, and many of the roads and hydroelectric dams across West Africa were built by American and Chinese firms.

own employees with new skills? Without much experience in modern manufacturing techniques, would a self-sufficient Fab City in an emerging market be doomed to remain decades behind the times—for example, stuck with labor-intensive hand-tools for metal and wood fabrication instead of contemporary automation? Could these Fab Cities ever work their way up to modern amenities, or would they remain trapped in the past with chisels and slide-rules?

Putting aside discussions around redistributed production, a more formal repair sector for emerging markets could also provide (or take away, if poorly executed) a substantial number of local jobs. The challenge is that formalizing repair will require a better working relationship between multinationals, which are generally based abroad and don't care about older product models, and the repair technicians, who regularly void warranties and use creative hacks to fix antiquated products. For example, consider West Africa's leading auto-mechanics cluster in Kumasi, Ghana. When computerized vehicles first came to the streets of Ghana around 2010, local auto-mechanics—who were mostly illiterate and trained through a hands-on apprenticeship model—had no idea how to properly interface with car computers. This lack of knowledge led to a slew of accidents related to the breaking systems in the first digitized model of Daf trucks; after auto-mechanics attempted to fix a computer bug by replacing the automatic breaks with incompatible manual breaks, a number of trucks suffered from sudden breaking failures. The subsequent onslaught of computerized vehicles caused a crisis among local auto-mechanics; in 2012, up to 40% of commercial drivers in the Kumasi metropolis used to be employed in auto-mechanics before switching jobs—likely due to the lack of education around computerized vehicles.⁴⁴

Multinationals may have a particular incentive to foster local repair-shops in the more remote regions of emerging markets, where reparability might make cost-sensitive customers more inclined towards brand loyalty. Companies could still manufacture their own products wherever they like, as long as those products can be repaired anywhere. This could lead to a distributed network of licensed repair technicians across emerging markets. As labor costs are considerably cheaper in emerging markets and consumer preferences tend towards used equipment, even companies that pursue a perpetual-lease model may find local repair (and maybe even local assembly) more cost-effective than shipping products back to the parent companies at the end of their lifetimes.

Yet again, the dearth of available case studies, the complexity of geopolitics, and the novelty of most Maker technologies leave us with more questions than answers. The future of the Maker Movement in emerging markets will depend considerably on protectionist policies and logistics costs, and whether major manufacturers ultimately find it advantageous to pursue the model of local manufacturing for local goods. Without further support, the underappreciated informal sector of SMMs in emerging

⁴⁴ Suame Magazine Industrial Development Organization, "Towards a new industrial village" report, (SMIDO: 2012).

markets will likely continue to expand without substantially upgrading their technical capabilities or providing new jobs— until they become obsolete, like the auto-mechanics of Ghana faced with computerized vehicles.

III. Conclusion

As discussed, the two Maker-Industrial models that have the greatest potential for creating a new, competitive manufacturing paradigm are those of redistributed production (following the model of Vertically-Integrated SMMs, Fab Cities, or some hybrid combination) and customization/repair. In our opinion, the most likely future will still feature a healthy high-volume manufacturing ecosystem—along with some mix of redistributed manufacturing, niche personalized production, and hopefully an increase in advanced repair-shops and SMMs across emerging markets. Particularly aggressive, protectionist policy-makers (both in the developed world and emerging markets) may even succeed in creating Fab Cities that produce a considerable quantity of local goods for local consumption—and thus trade data rather than products with the rest of the world.

Further investigation is recommended to explore the laws and capital constraints underlying modern, localized production—and how all these elements might shift and develop across different global regions. Markets such as Germany, China, and Japan already feature high-tech and prosperous ecosystems of SMMs—in contrast to the USA, where multinational, high-volume manufacturers rather than SMMs dominate the market. Countries like Italy that already provide strong local support for SMMs and artisanal production may be more inclined towards creating Fab Cities than the USA, in which the concept represents a radical shift. As discussed, emerging markets have a particular incentive to support repair and upgrade existing local manufacturing capabilities in an effort to provide decent jobs—although this may not be possible without considerable partnerships with multinationals. In a world of increased automation, both SMMs and repair/customization shops could support many new jobs in non-metropolitan areas—especially in emerging markets.

In the USA, government-sponsored defense manufacturing could provide a fertile testing ground for experimentation with redistributed production models and OSH standard-development—similar to how government defense programs sponsored research into open internet protocols in the early days of ARPANET. Security will likely be a significant concern; this may encourage the employment of novel cryptography tools such as the blockchain, to decentralize trust and enable selective exchanges of information to multiple parties.

Our final questions revolve around what may be a trade-off: would it make sense to support a less economically competitive production model for the sake of social benefit?

Will this necessarily be a trade-off, or could an efficient redistributed manufacturing model establish new niche markets and/or compete on a global scale?

We share the skeptical realist's view that today's Maker Movement has not yet shifted the current production paradigm. While this Movement may have enabled any decently-educated person to create some one-off product, the barriers to large-volume manufacture of that product have not changed significantly. We caution stakeholders not to get too caught up in the idealism of the Maker-Industrial Revolution, but we also advise everyone to consider—and, perhaps, to work toward—future possibilities. After all, to paraphrase Mark Hatch and Neil Gershenfeld, in the early days of computing no one believed that laypeople would have any need for personal computers.

Even the most “democratic” of technologies are fundamentally tools rather than determinants of organizational and economic structures; we can use the tools of the Maker Movement to create a world of self-sufficient Fab Cities, or we can follow the lead of MakerBot and GE and foster high-volume manufacturing in automated megafactories in China or India. Both models might even be equally profitable, depending on policy structures and unknown variables such as global warming. To conclude, we advise stakeholders to carefully consider what kind of future we want to make for ourselves—and then to employ our vast array of Maker tools accordingly.

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Appendix

Appendix 1: Maker Movement Compendium

Here is a link to an extensive Googledoc compendium on Maker Movement research:
<http://goo.gl/Ceakh7>

Appendix 2: A Tale of Four Repairable Tractors

Since tractors—unlike most consumer electronics— are necessarily robust and repairable products, we present four different tractor business models for comparison.

In contrast to Komatsu’s model of centralized manufacture and repair, the fully-OSH initiative Open Source Ecology released all designs for their *LifeTrac* tractor for anyone to fabricate from scratch. Sadly, we have only found a handful of groups who have succeeded in building this product—and even fewer are regularly using it on their farm. Critics of Open Source Ecology claim that their movement falls into the Trekkie fallacy of believing that people have a desire to make their own complex tools, whereas most professional farmers may lack the interest and know-how to produce their own tractors. (The Open Source Ecology movement isn’t particularly bothered by this fact, since they forecast a post-apocalyptic near future in which humanity will be forced to start over from basic resources. Such a prognosis is outside the scope of our paper, so we will simply discuss the current status of the LifeTrac.)

The Cuban-American company Cleber LLC claims to subscribe to the same OSH mission as Open Source Ecology for the Oggun tractor, although their manufacturing model is more similar to the idea of Micro-Factory Retailing (as described in the Localized Production section). Like the LifeTrac, anyone who wants to make/repair an Oggun should be able to find all necessary documentation online. Yet in contrast to relying upon individual tractor-fabricators, the company intends to professionally manufacture their wares across a network of franchised SMMs.⁴⁵ Following the business model of the OSH Arduino microprocessor, Cleber likely believes that the start-up costs and expertise required for tractor manufacture will keep casual pirates from copying their product—and encourage any serious SMMs to foster more formal connections with the parent company. Perhaps Cleber, like Arduino, also intends to continue research and development in house, disseminate new ideas amongst their franchised SMMs, and foster an excellent reputation for quality control— further encouraging local SMMs to enter into a legal agreement with the inventors rather than illegally manufacture unlicensed tractors.

Cleber will likely employ this strategy to train their tractor SMMs in Cuba, where they can also take advantage of a highly skilled, informal vehicle-repair sector that succeeded in keeping vintage cars running for years during the USA embargo— which deprived Cuba of any licensed spare parts.

Following Cleber, would major manufacturers like Komatsu find it advantageous to pursue a similar strategy of providing tools for SMMs to make low-tech tractor components?

On the closed-source tractor side, John Deere has pursued an even more aggressive patent enforcement strategy than Komatsu; the company fought in USA courts to

⁴⁵ Cleber LLC, “Oggun Open Source Manufacturing Model,” <http://cleberllc.com>, (2016).

declare all third party modifications and repairs illegal under the Digital Millennium Copyright Act (DMCA)—even for customers who have purchased their tractors outright, unlike Komatsu’s perpetual-lease model.⁴⁶ While it is likely difficult for John Deere to keep track of users’ modifications, this may change if they follow Komatsu’s lead and incorporate IoE sensors into their tractors—so they could know what happens to any component in any tractor at any time, and prosecute accordingly. Luckily for OSH enthusiasts, John Deere has encountered serious legal opposition to their claim to perpetual tractor ownership. Of course, John Deere’s vision of the perpetual-lease model is in direct opposition to the Maker ethos of user modification.

Komatsu currently takes a more moderate approach to third party repair on their perpetual-lease tractors. Since they have all the real time data streams about what parts need to be replaced when and how the machines are being used, they promise to buy back their tractors after 5 to 10 years at a guaranteed good price if owners do all the recommended maintenance at licensed shops, and use the machines according to guidelines without overtaxing them. They thus incentivize internal repair/customization rather than forcing the issue (like John Deere) or allowing any interested third party to participate (like Cleber and Open Source Ecology).

For reference, here is a table describing these four models for tractor manufacture and repair:

	John Deere	Komatsu	Cleber	Open Source Ecology
Style of Production	Central factory	Central factory	Localized, networked SMMs	One-off
Repair/maintenance Strategy	Required to be licensed only	Encouraged to be licensed only	Localized repair-shops	Personalized
Openness	Closed Source	Closed Source	Open Source, perhaps with company support for SMMs	Open Source

We deem it too early to draw conclusions about which of these business models will be the most successful—since Cleber and Open Source Ecology are relatively new tractor producers, and neither Komatsu nor John Deere have rolled out IoE tractors on a large scale. Nonetheless, we believe that Cleber’s model may prove more viable than Komatsu’s in emerging markets—for reasons stated in the next section.

⁴⁶ Kyle Weins, “We Can’t Let John Deere Destroy the Very Idea of Ownership,” *Wired*, <http://www.wired.com>, (April 21, 2015).

