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White Paper

3D Printing: A Guide for Decision-Makers

In collaboration with Mitsubishi Chemical Holdings Corporation

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Contents

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Foreword

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Emerging technologies are shaping our societies. Digitalization is affecting a myriad of aspects, from how people interact with each other to how they search for and buy products. The Fourth Industrial Revolution encompasses a novel technology that has the potential to make fundamental changes to the ways products are made and distributed: 3D printing (3DP).

3DP might revolutionize the way products are made by disrupting manufacturing patterns, creating novel visual forms that were never possible before, enabling mass customization and offering new pathways to increase the circularity of products. At the same time, 3DP may provoke unintended consequences, such as potential workforce displacement, impacts on trade volumes and supply chains, fiscal and non-fiscal challenges to customs at borders, and room for intellectual property and legal violations.

The hype over 3DP adoption, including the prediction of "print at home anything", has not become reality. Consumer 3DP has not gone beyond do-it-yourself enthusiasts, and 3DP revenues were less than 0.1% of global manufacturing revenues in 2018. At the same time, 3DP global revenues have been rapidly growing at an average annual rate of 26.9% over the last 30 years (Wohlers Associates, 2019).

The future of 3DP is evolving and, as such, its impact on different realms is unknown. This White Paper explores these realms and serves three functions. First, it presents broad scenarios of how the future might look like in five areas – manufacturing, trade and customs, supply chains, legality and the environment – if 3DP becomes more widely adopted. Second, it suggests leading indicators to monitor, predict and prepare for higher 3DP adoption. And third, it discusses the relevance of existing policy instruments through the lens of 3DP to point to policy changes that might be needed in the future.

The World Economic Forum drives the effort by using its platforms and multistakeholder network to share insights, trigger actions and develop future-proof policies by government and businesses for the further adoption of 3DP globally. This paper is part of the TradeTech initiative of the World Economic Forum. It has been produced by the Platform for Shaping the Future of Trade and Global Economic Interdependence.

The uncertainty of the scale of 3DP adoption and the effort required to establish the suggested indicators highlight the need for further public-private cooperation.

Executive summary

3D printing (3DP) is a new and growing area that deserves the attention of business leaders and policy-makers. Understanding the state of this technology, projected future scenarios based on its broad adoption, and how to monitor and prepare for the technology's positive and negative effects are important considerations.

3DP presents several novel opportunities, the most ubiquitous of which is prototyping. 3DP allows for decentralizing manufacturing by making parts close to consumption. Previously difficult-to-make designs can be easily 3D-printed. This enables tantalizing possibilities; for example, hollow or honeycomb structures can reduce lifecycle costs in many applications, such as aviation. Mass customization may become a reality, with 3DP as key enabler. 3DP is poised to disrupt numerous markets, including automotive, healthcare, construction, fashion and food. The technology is being advanced by passionate, talented players who are inventing newer and faster ways of 3D printing, exploring new materials to print with and developing new business models based on the technology's benefits.

3DP was invented over 30 years ago, but it has not yet made noticeable inroads in manufacturing; in 2018, 3DP revenues were less than 0.1% of global manufacturing revenues (Wohlers Associates, 2019). Decision-makers in the manufacturing world treat 3DP as yet another tool and perform return-on-investment and qualification analyses, just as they did for other novel technologies, such as computer numerical control. Further, instead of treating 3DP as a stand-alone technology, they have begun to integrate 3DP-related decisions within corporate, product and engineering/operations strategies because of the technology's disruptive nature. Governments and intergovernmental organizations have the opportunity to develop regulatory strategies to maximize the benefits and mitigate potential unintended consequences.

Broad 3DP adoption could have important effects in several areas, such as manufacturing, trade and customs, supply chains, legality and safety, and the environment and sustainability. Workforce displacement/replacement is a potential consequence of 3DP adoption in manufacturing. 3DP-enabled decentralization of manufacturing could affect trade volumes. Supply chains might be shortened by 3DP, potentially affecting regions that rely on low-cost labour. Intellectual property and legal challenges can be expected to increase because of the ease of transmission and copying of 3DP designs. Finally, the opportunity exists to create environmentally sustainable manufacturing systems based on 3DP. Existing policies need to be analysed and perhaps revised to meet these challenges.

The pace of adopting 3DP has been slow to date. While revenue growth is increasing rapidly, the extent to which the technology will penetrate mainstream industries and markets in the future is unclear. Further, in many cases it is also not clear whether the impacts will happen at all, or if they do, which of two opposing outcomes might happen: for example, will trade volumes increase or decrease as a result of eventual 3DP scale-up? To navigate these uncertainties, several leading indicators can be monitored to explore possible outcomes. Monitoring those indicators could become part of the planning processes of businesses and national and international agencies.

Why should business leaders and policy-makers care?

3D printing (3DP), a novel technology considered to be part of the Fourth Industrial Revolution (Schwab, 2016), has the potential to make significant and rapid changes to the way products are manufactured and distributed. To stay ahead, business leaders and policy-makers need to understand the technology and its implications to develop forward-looking strategies and policies for their businesses and stakeholders. Three key benefits of 3D printing are outlined in Box 1.

3DP enables unique approaches in the following:

- Efficiency improvements and product novelties: Products can be made in far fewer steps than conventional manufacturing, going directly from raw materials to finished products. Buildings can be custom-built quickly using 3DP of construction materials. Novel and more robust geometries and reduced waste can be achieved.

- Products with substantial societal impact: These include 3D bio-printed body parts and organs that could save and improve lives, pills that dissolve at the right time to ensure the most efficient absorption in the body, and food that is customized to individual nutritional needs.

Existing approaches to manufacturing may be turned upside down. 3DP could promote highly decentralized manufacturing, with low or no inventory and short supply chains. Mass customization could finally become reality in consumer products and medicine.

The adoption of 3DP has been limited by the high unit cost of 3D-printed goods and general growing pains for deployment in manufacturing, such as qualifying printing processes and products. But 3DP has been more widely adopted in medical, aerospace and automotive areas, primarily for prototyping and tooling. Some niche areas have gone deeper, using 3DP to make final products, such as dental aligners and hearing aids. Global revenues from 3DP are growing fast year over year, but 3DP revenues constituted less than 0.1% of 2018 global manufacturing revenues (Wohlers Associates, 2019).

3DP is an area to watch because of its ability to disrupt production approaches. It offers the opportunity for democratizing production. For example, regions and countries with a talented or trainable workforce could jump-start their manufacturing base with low capital investment. As discussed later, however, the potential for high negative effects in several directions exists. Policy issues in trade and customs need to be addressed early. Businesses need to adopt specific strategies in order to successfully exploit 3DP. Finally, all of these could become urgent if the expansion of 3DP accelerates or if significant disruptive innovations occur in the technology.

Box 1: The three Ws

Three benefits of 3D printing concern “**what**”, “**when**” and “**where**”:

What: Only required quantities of products are printed (with the option of customizing every single product for the buyer), reducing product waste due to excess production.

When: Products are made just in time (after the order is placed), reducing inventory levels and delivery times.

Where: Products are made close to their consumption, reducing the logistics of delivery and CO_2 emissions.

The current state of 3D printing

What is 3D printing?

The phrases "3D printing" and "additive manufacturing" are often used interchangeably by practitioners. This paper will use 3D printing, or 3DP, to refer to this technology, as this is the underlying enabler that has broader applications, while additive manufacturing (AM) is specific to manufacturing. The International Organization for Standardization's American Society for Testing and Materials 52900 terminology standard defines AM as the process of joining materials to make parts from 3D model data, usually layer by layer.

Several techniques produce parts in layer-by-layer fashion by extruding, photocuring, fusing, jetting or laminating materials (Redwood, Schöffer & Garret, 2017). These techniques construct a part by virtually slicing it into extremely thin slices and then building up the part in the 3D printer by repetitively building one layer on top of another, until the entire part is built up (Figure 1). This is dramatically different from conventional manufacturing methods (for example, subtractive methods – see Figure 2). Today, plastic, metal, ceramic, glass, composite and biomaterial parts can be 3D-printed.

With thoughtful redesign, or use of tools such as generative design (Generative Design, n.d.), 3D-printed parts can outperform their conventionally made counterparts in terms of weight, strength or general fitness for purpose (though weak inter-layer strength is a concern, and is a focus of research). Several components previously made in multiple manufacturing steps can be combined into a single-step production, reducing supply chain risk, cost and lead time. In the digitally driven processes of 3DP, manufactured goods could be rapidly updated to create new versions.

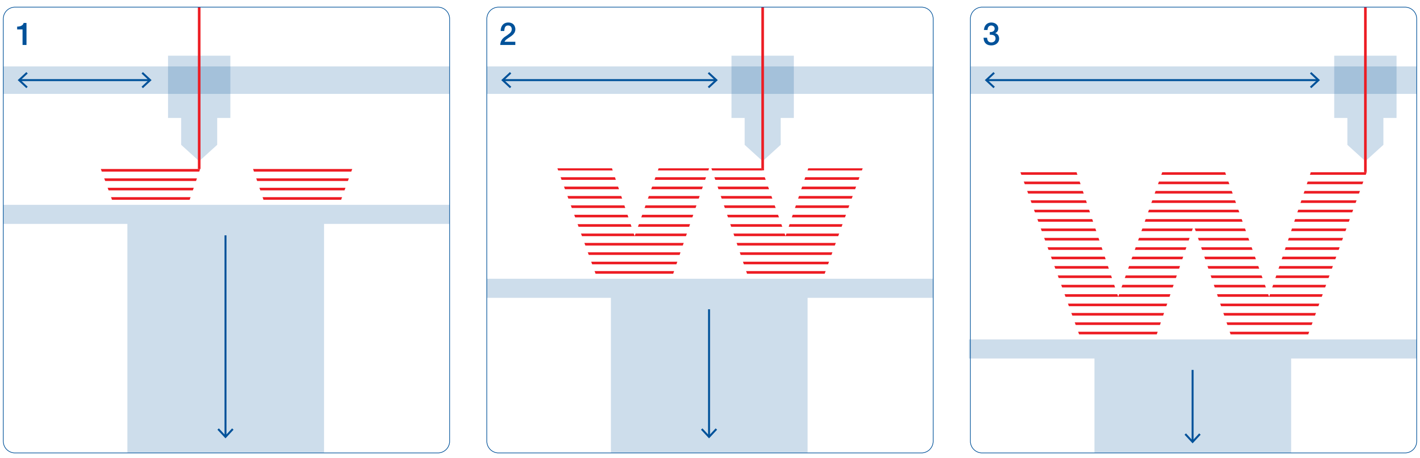
3DP technology has existed for over 30 years, with an early patent in the 1980s (Hull, 1984). Since then, 3DP has been touted as capable of transforming how goods are produced, with a big hype in the period 2011-2014 (Basiliere & Shanler, 2019). The early hype has died down, but the technology continues to evolve, with many new printer manufacturers focusing on metals and desktop units. Manufacturing of 3D printers picked up after 2008, when early patents began to expire. Over the past decade, the number of printer manufacturers has risen steadily.

Consumer 3DP generally has not gone beyond do-it-yourself enthusiasts, even though the number of online resources available for sharing 3D models and for print jobs has increased over the years. Key reasons for this lack of widespread adoption are the difficulty of creating 3D models to meet individual needs, and capital and operating costs of devices with required functionality. The high-skill needs of computer-aided design (CAD) and the unique skills required to design 3D-printable models pose a high barrier. Advances in artificial intelligence (AI) may lower this barrier through broad availability of consumer-friendly apps.

Current applications

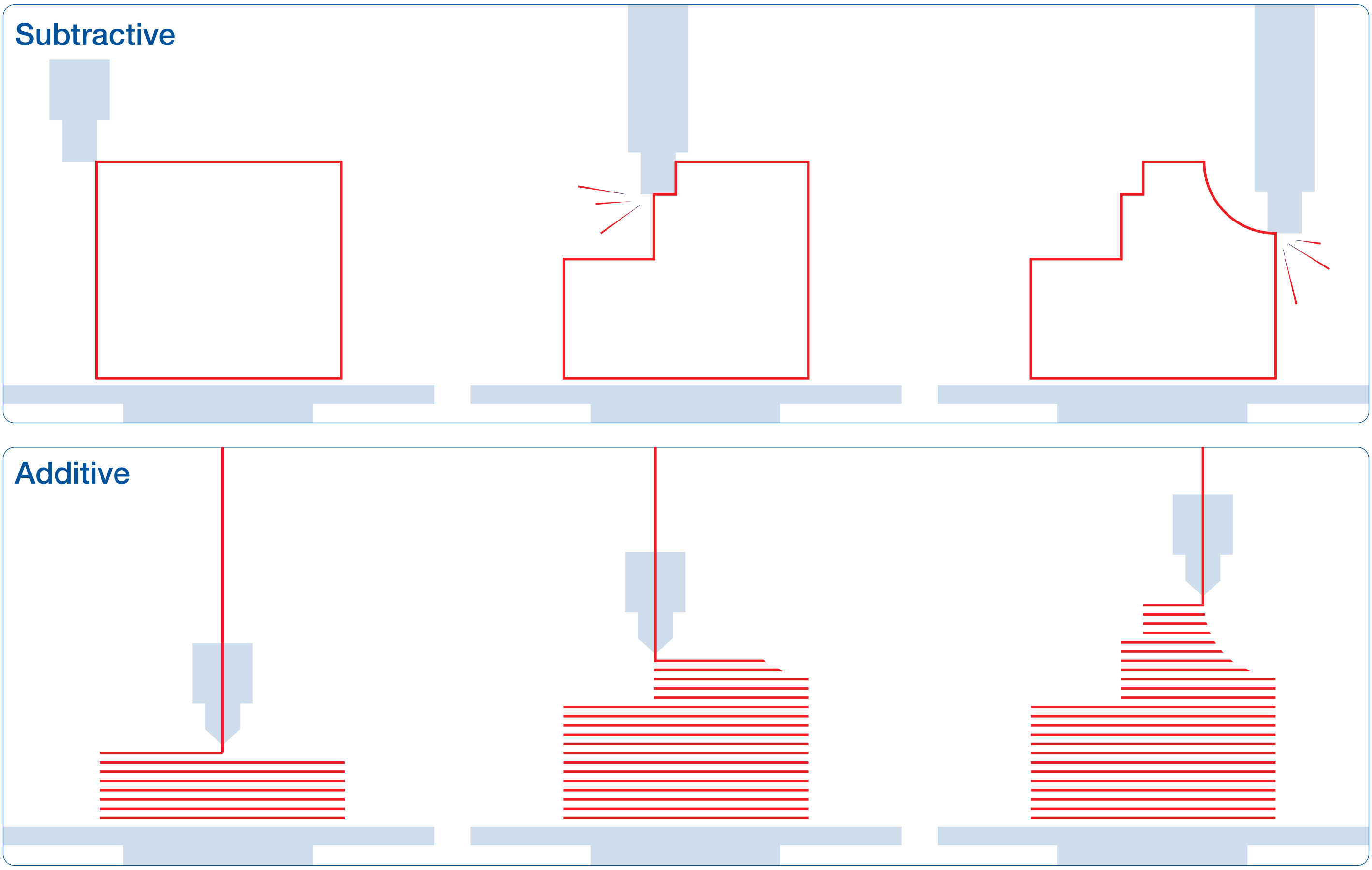
The most common manufacturing applications for 3DP are prototyping and tooling (jigs and fixtures). Designers and architects prototype their creations and refine them through quick iterations before moving beyond prototyping. In May 2019, Heineken reported a 70-90% lead time and cost reduction using low-cost desktop 3D printers to produce tooling (van de Staak, 2019). A growing application is the making of spare parts on demand, instead of manufacturing and stocking ahead of time. Thus, 3DP is complementing traditional manufacturing. The segment of 3D-printed end-use parts, while small, is growing: over the past 10 years,

Figure 1: 3DP – The layer-by-layer build-up of parts



Source: Based on 3D HUBS, "Introduction to FDM 3D printing", https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing

Figure 2: Schematic illustration of subtractive and additive (3DP) manufacturing methods



Source: Based on 3D HUBS: "3D Printing vs. CNC machining", https://www.3dhubs.com/knowledge-base/3d-printing-vs-cnc-machining

production of end-use parts has increased from 15.6% to 28.4% (as a percentage of parts produced by 3DP facilities), according to the 2009 and 2019 editions of the *Wohlers Report* (Wohlers Associates, 2019).

Owing to the needs of individual customization, dental aligners and hearing aids are increasingly produced using 3DP, and surgical guides are also 3D-printed. The trend towards 3DP hubs, known as FabLabs, is increasing; they host a variety of 3D printers and fulfil orders for printing as a service. This allows manufacturers and others to experiment with 3DP without making capital investments in the printers. UPS is an early entrant into the 3DP business with 3D printers at many of its US depots, mainly serving small businesses. A small do-it-yourself ecosystem exists among prosumers, the home users beyond hobbyists. The 3DP industry is now in the throes of qualifying its machines and processes for broader aerospace and automotive applications.

Future applications

Along with the internet of things (IoT) and AI, 3DP could enable truly digital manufacturing. Data from the IoT could drive digital manufacturing processes, AI could convert the data into information for decision-making, and 3D printers will make parts from digital design files.

In one potential scenario, as 3DP adoption grows, an aggressive scaling of decentralized manufacturing may occur in automotive, aerospace and other areas. The use of 3DP in these areas can be expected to expand into the manufacturing of functional components. The adoption of making spare parts on demand may skyrocket, decimating inventories of pre-manufactured parts everywhere. In fact, the technology has the potential to shake up the manufacturing sector (D'Aveni, 2018).

Another scenario is that 3DP use in construction could grow, fostered by initiatives such as one in Dubai (Jezard, 2018), which projects that 25% of Dubai's buildings will be 3D-printed by 2025. Similarly, China has started experimenting in construction, having already 3D-printed a six-storey apartment building and a 1,100 square metre villa (Stott, 2015).

Additional scenarios could include opportunities for mass customization in food, nutrition, fashion, automobiles, footwear and toys, among other sectors. Bioprinting may replace organ donation and become the primary source of artificial limbs. Use of 3DP could become standard for producing custom implants and prosthetics.

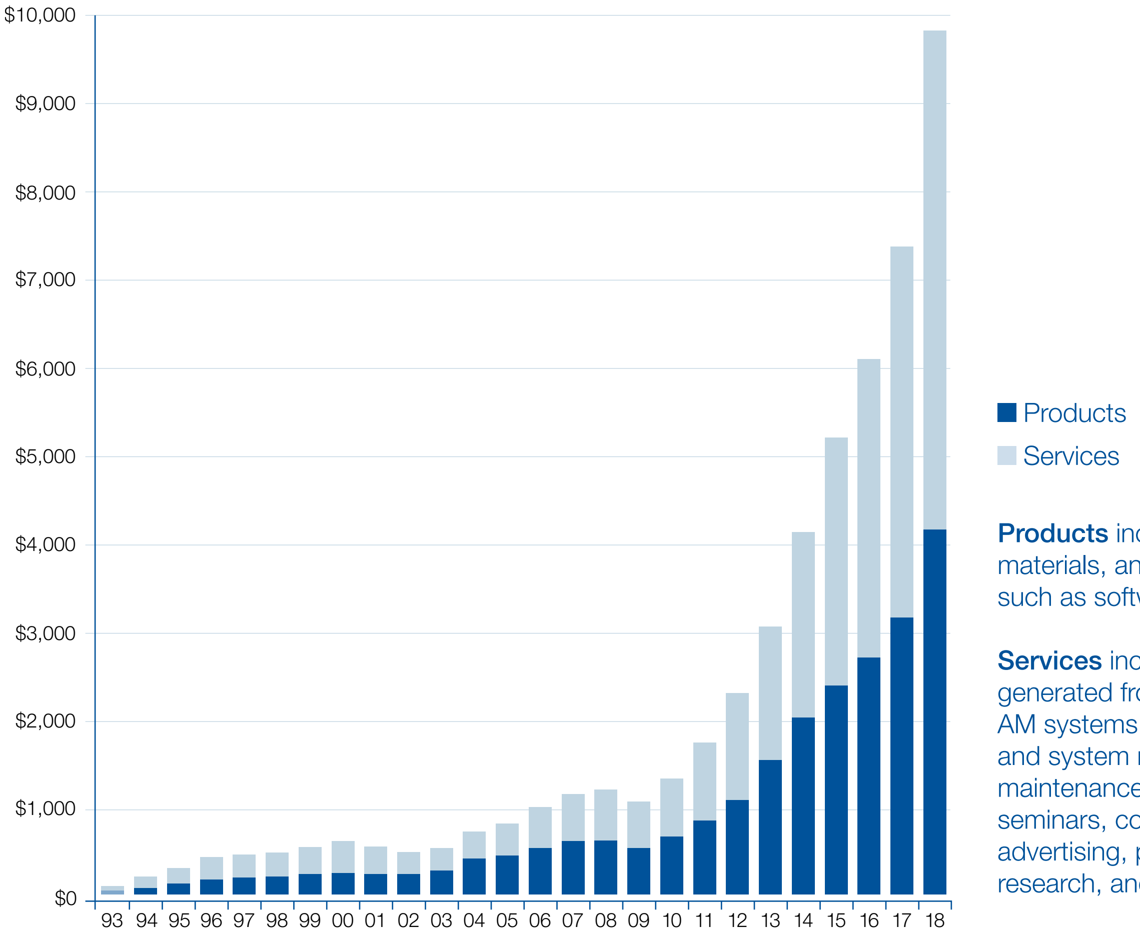
3DP hubs might proliferate, and consumer access to 3DP could expand, allowing a much larger cross section of the population to experiment with it. Home 3D printers and FabLabs might spawn a new generation of crafts, just as the sewing machine did (Lange, 2014).

From all these scenarios, new, creative business models are likely to emerge, leveraging the benefits of 3DP and thereby creating further opportunities for disruption. These models are expected to further increase the share of services in 3DP revenues.

The pace of adoption

While 3DP revenues have been growing fast (Figure 3), 2018 global revenues totalled $9.8 billion, a rather small amount compared to global manufacturing revenues of $12.8 trillion. The potential for additive manufacturing to attain 1% of global manufacturing revenue in the next five years is five times greater than the most optimistic projections, as reported in the 3D Hubs *3D Printing Trends Q1 2019* report (3D Hubs, 2019).

Figure 3: Global 3DP revenues (in million $)



Products include AM systems, materials, and aftermarket products, such as software and lasers.

Services include revenues generated from parts produced on AM systems by service providers and system manufacturers, system maintenance contracts, training, seminars, conferences, expositions, advertising, publications, contract research, and consulting services.

Source: Wohlers Associates, 2019

Most experts agree that 3DP is likely to be deployed in niche or custom products, rather than taking the place of established production approaches (e.g. for everyday plastics). Experts differ on when 3DP revenues will make a dent in global manufacturing revenue, with opinions ranging from 10 to 30 years.

Most products are manufactured in factories. To achieve scale-up, manufacturing must adopt 3DP on a large scale. Currently, 3DP is mainly used for rapid prototyping, tooling and low-volume production. What prevents 3DP from scaling up quickly in manufacturing? Some of the reasons are:

- The technology is not always reliable in terms of reproducibility and yield, for example, though reliability is improving rapidly, especially in high-end printers.

- The unit cost of making a 3DP part is higher than those for traditionally volume-manufactured goods, making 3DP more suitable for low-volume products.

- The strong perception is that 3DP processes are slow; for true comparison, however, end-to-end production time – from raw materials to finished products – must be considered.

- Manufacturers consider that 3DP is yet another tool, and that it must prove its mettle in process/quality control. This takes time.

- Manufacturers need data on the benefits of 3DP to their products, but the data will not be available until 3DP is widely adopted in their sectors. This is a circular situation.

- 3DP enables decentralized manufacturing. But several barriers to move to distributed/decentralized manufacturing exist, including the investments needed (Rauch, Dallinger, Dallasega & Matt, 2015) and high post-processing labour content. Logistics costs for light products seem not significant enough to trigger decentralized manufacturing near consumption markets (Freund, Mulabdic & Ruta, 2019).

- Turning the promise of mass customization to reality is not simple. Only 10% of online shoppers use product customization options (Spaulding & Perry, 2013), as it does take effort for consumers to provide information required to customize products.

- Scaling up depends on the availability of skilled labour and on process standardization, both of which will take time to achieve for a new technology.

- Policy issues (Ferracane, 2016), such as those for certifying 3DP parts for healthcare applications, take time to address.

What can be done to help the scale-up of 3DP? For this, deeper, strategic realignments on 3DP's fundamental capabilities are needed, in addition to integration with supply chains and business models. The reflections in Figure 4 are critical for stakeholders to make strategic realignments.

Figure 4: Key questions for developing strategies to adopt 3DP in manufacturing

Corporate Strategy

In what respects do your manufacturing capabilities drive your competitive advantage?

How do trade barriers, transportation challenges, and localized requirements affect your ability to serve your markets?

How can you take advantage of decentralization and shorter supply chain opportunities?

How do you mitigate IP risks of a digital, decentralized supply chain?

National Strategy

How do you promote 3DP within your region / country?

What investments are needed?

How do you create the needed ecosystem?

How do you create a trained workforce?

How do you work with intergovernmental agencies to address cross-border challenges?

Product Strategy

How can you leverage fast turnarounds, low fixed costs, and high marginal costs?

Where can you leverage mass customization?

How can you take advantage of innovative, new geometries, and ease of per-part customization?

How do you phase in new 3DP products vs replacing existing ones with 3DP?

Engineering & Operational Strategy

How do you integrate 3DP within the entire product lifecycle?

What software and process monitoring systems are needed?

How do you qualify the new materials and processes?

How do you take advantage of the lower material/inventory needs of 3DP?

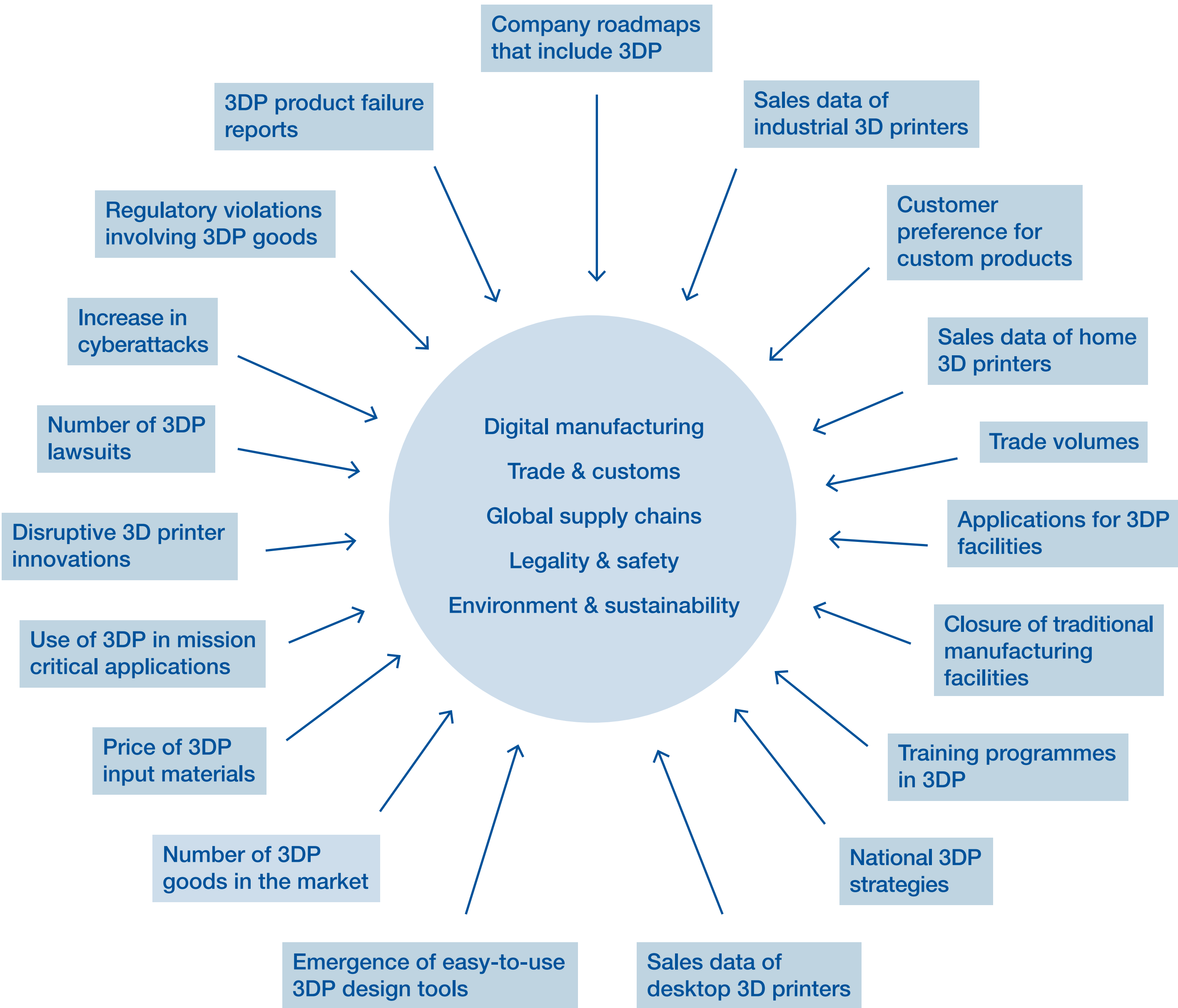
Note: IP = intellectual property
Source: World Economic Forum and Mitsubishi Chemical Holdings Corporation, with contributions from Formlabs and Bain & Company

How can businesses and governments prepare for the future?

3DP, like other Fourth Industrial Revolution technologies such as AI, blockchain, IoT and autonomy, needs to be addressed, as business strategies and appropriate policies have failed to keep pace with the growth of these technologies. Businesses and governments are responsible for shaping the trajectory of the technology for positive outcomes. 3DP can affect multiple areas, including the five covered in this paper: manufacturing, trade and customs, supply chains, legality and safety, and the environment and sustainability. Many of these areas require early preparation, considering the time needed to develop targeted policies and regulations. The policies and regulations can serve as enablers for the legitimate development of 3DP, while providing a level playing field and setting out a robust regulatory mandate and associated mechanisms against potential misuses.

Figure 5 presents leading indicators that could be monitored as they can be used to gauge impact on the five areas explored in the subsections that follow. Table 1 lists the leading indicators and their significance, and the actions that might be taken to predict upcoming trends and challenges in the five areas.

Figure 5: Leading indicators to monitor trends of 3DP adoption and upcoming challenges



Source: World Economic Forum and Mitsubishi Chemical Holdings Corporation

While it would be important for business leaders and policy-makers to project potential outcomes of the growth of 3DP, the outcomes cannot be projected with certainty – they may or may not happen in some cases, and in other cases the opposite may occur. An example of the latter is global trade. There have been suggestions on both sides, namely those that argue that global trade will decline (Leering, 2017) and those that predict the opposite (Freund, Mulabdic & Ruta, 2019). Because of these uncertainties, it is important to watch for signs of what might happen, and economic models can help quantify this. Yet 3DP economic models are generally lacking, with some first attempts in this direction (Abeliansky, 2019).

Table 1: Leading indicators, their significance and how to use them

Leading indicator	Significance of indicator	Suggested actions
Company roadmaps that include 3DP	When 3DP appears on company roadmaps, plans to decentralize and bring production close to consumption might occur	Review whether the roadmap implicates moving or closing facilities; look for projections of workforce changes
Sales data of industrial 3D printers	An increase in the volume of industrial 3D printers might suggest their potential use either in making niche products or in replacing traditional manufacturing equipment	Examine the market segmentation of customers buying the printers; review which ones include traditional manufacturers
Consumer preference for custom products	As customers show increased preference for bespoke products, mass customization opportunities increase for 3DP	Identify product opportunities for mass customization using 3DP; look for new business models that emerge to benefit from these
Sales data of home 3D printers	An uptick in household 3D printer purchases could result in increased household plastic waste and reduced shipping volumes	Track statistics of 3DP material sales to households to understand if the printers are being actively used to make parts at home
Trade volumes	Indicators such as the World Trade Organization (WTO) trade barometers could signal increasing or decreasing trade trends in goods and services, giving a first indication of whether looking further into trade statistics of intermediary products is needed Trade statistics from the Organisation for Economic Co-operation and Development (OECD) Trade in Value Added (TiVA) database could signal a reduction of foreign value-added content of exports, which could suggest increasing 3DP uptake in consumption markets	Look for trade volume reductions in intermediary goods for which demand in final goods in consumption markets is still high, to identify early signs of decentralization
Applications for 3DP facilities	As the number of printing locations increases, the potential for production near consumption increases	Check to see if products from the facilities will serve a local market, and if so, whether the products displace current products

Leading indicator	Significance of indicator	Suggested actions
Closure of traditional manufacturing facilities	Closures of traditional manufacturing facilities result in displacement of the workforce	Check if closures are related to trends in target consumer markets picking up 3DP production close to consumption
Training programmes in 3DP	Introduction of programmes at educational institutions to train students in 3DP is in anticipation of demand for such expertise, and therefore of changes in employment patterns	Review enrolment and graduation rates in formal and informal courses to estimate availability of trained 3DP workforce and the shift in skill needs
National 3DP strategies	As more nations consider 3DP as part of their growth strategy, the prospects for decentralization grow	Explore how to meet the needs in the national strategies with existing/ expanded 3DP facilities; study the proposed product portfolio to estimate decentralization
Sales data of desktop 3DP printers	An increase in desktop printer sales signals widespread use in smaller factories and FabLabs, which could suggest an increase in the trade in digital goods	Study the market segmentation of desktop 3D printer sales, notably between industrial and FabLab use, to understand uptake in each
Emergence of easy-to-use 3DP design tools	Design skills pose a barrier to adoption; tools and online resources that lower the barrier through ease of use will promote 3DP adoption	Follow sales of the new tools and the number of designs made/ downloaded and parts printed using the new tools
Number of 3DP goods in the market	More 3DP goods appearing in the market is indicative of changes in the supply chain	Monitor supply chain reports on products that are replaced by 3DP goods to understand the effect of the supply chain on those products
Price of 3DP input materials	Proprietary input materials keep prices relatively high today; a drop in prices could signify demand or commoditization	Track increase in sales volume of 3DP input materials due to drop in price, to estimate usage increase
Use of 3DP in mission-critical applications	When critical parts, such as for aircraft, are 3D-printed, the risk of cyberattacks on the printers increases	Track parts being produced using 3D printers in critical sectors, such as aviation, to evaluate the need for standards/control
Disruptive 3DP innovations	Innovations that speed up printing or reduce printing cost will increase adoption	Monitor sales data of new 3DP products that use disruptive innovations
Number of 3DP lawsuits	Lawsuits related to 3DP increase with growing IP violations or other legal issues related to 3DP	Examine the segmentation of the lawsuits, in terms of the core reasons, to prepare for changes in laws applied to 3DP
Increase in cyberattacks	More cyberattacks suggest increasing vulnerable installations	Examine correlations between the increase in attacks and the vulnerability of 3D printers
Regulatory violations involving 3DP goods (e.g. guns)	Printing of regulated products could signal increased access and misuse of regulated products	Monitor regulatory violations for increase in use of 3DP to prepare for methods to curb the use
3DP product failure reports	Increase in 3DP product failures could foretell upcoming legal challenges or class action suits	Compare 3DP failure reports with traditional product failure reports to monitor trends

Source: World Economic Forum and Mitsubishi Chemical Holdings Corporation

The following subsections outline the challenges in the five areas.

Prepare for digital manufacturing with 3DP

Digital manufacturing is driven by data – design files provide 3DP part and processing information, IoT devices generate data on processes, and AI software ties these together by creating an efficient production control system. The World Economic Forum has identified 26 factories around the world that are showing the way in adopting these Fourth Industrial Revolution technologies (World Economic Forum, 2019). The ideal digital manufacturing world will be decentralized and enabled by the "three W" benefits of 3D printing (Box 1), have low inventory, will be scalable on demand and will have low waste/scrap and undesirable rejects. The supply chain will be shorter, corresponding to a smaller bill of materials.

An unintended outcome of digital manufacturing with 3DP could be the replacement or displacement of the workforce, which would mainly result from decentralization and reshoring. Decentralization is enabled by 3DP; smaller facilities in many locations may replace a single large centralized manufacturing facility that employs large numbers of local labourers. In the case of 3DP, several smaller FabLabs could replace a large manufacturing centre. Reshoring is a special case of decentralization, where facilities are created in areas with a historically higher cost of labour in order to meet local demand for products instead of importing them from low-cost labour areas. In contrast, replacing a production line in a traditional factory with 3D printers is like adopting other manufacturing automation approaches, which in general have a smaller impact than layoffs due to factory shutdowns.

The introduction of 3DP could reduce the labour intensity of production, as projected by the Heckscher-Ohlin framework (Wikipedia, 2019). A recent study by the World Bank analysed data for 35 products that were partially 3D-printed and suggested that there might be a "reshuffling in comparative advantage from labour abundant/ developing economies to capital abundant/advanced economies (Freund, Mulabdic & Ruta, 2019)." Some recent developments, however, show that labour cost might still be a decisive factor when deciding whether to reshore certain tasks, even if they involve 3DP (Box 2).

On the other hand, 3DP, with its accessibility and scalability, could lower the barriers to entrepreneurship in some manufacturing sectors. 3DP is accessible because it relies on increasingly user-friendly software and hardware that do not require extensive training to operate. Also, the low initial and incremental capital costs of manufacturing with 3DP promote scalability, especially when compared to transitional manufacturing tools which are often more expensive (e.g. computer numerically controlled machines). All else being equal, the anticipated increase in the competitiveness of small firms that use 3DP to make physical products will create a range of opportunities for entrepreneurs, workers and investors who can adapt to this new manufacturing paradigm.

Box 2: How is reshoring playing out today?

3DP is a critical enabler for mass customization of products. Will this foster a trend towards "reshoring", or bringing production back to regions where the products were originally designed and manufactured but later moved to lower-cost regions? It sounds likely, but the following two cases do not support this trend.

Align Technology, one of the early adopters of 3DP, leads the market for dental aligners with its product Invisalign. Dental scans are taken on patients in dentists' offices around the world, sent to Costa Rica for treatment modelling and planning, and about 1.6 million aligners are 3D-printed in Mexico every week and distributed from there (O'Neill, 2018).

Adidas has experimented since 2016 with digital manufacturing in "Speedfactories" in Ansbach, Germany and Atlanta, USA. These factories included robots and 3D printers to decentralize their manufacturing process. But Adidas recently announced it is moving the Speedfactories to two of its suppliers in Asia (Coldewey, 2019).

What actions could business and policy-makers take for digital manufacturing?
Business: Train, retrain, and offer internships and short courses on 3DP
Policy-makers: Make early-age education in 3DP available, as well as university programmes and vocational training with a 3DP focus

Plan for impacts in trade and customs

3DP can affect trade volumes and the structure of global value chains, driven by production scalability, 3DP uptake and logistics costs. Opinions differ on whether trade volume will increase or decrease due to 3DP (Box 3). Opposite perspectives might be explained by different scopes of analysis, whether the focus is on trade in final goods or intermediary inputs. Three trends seem very likely, however, if 3DP scales up globally: (1) a shift in physical trade flows from finished goods to 3DP input/raw materials, such as filaments ("ink"); (2) a reduction in trade in intermediary products, if 3DP is highly adopted and results in production of final goods directly; and (3) an increase in cross-border electronic transmissions.

3DP raises several questions for digital trade, defined as digitally-enabled transactions of trade in goods and services that can be digitally or physically delivered, and that involve consumers, firms and governments, following the definition by the OECD. The following three areas are worth exploring to determine the relevance of existing trade instruments in the scenario of increased cross-border transmissions of 3DP CAD files:

– Classification: How to classify 3DP CAD files, as goods or services

– Rules of Origin (RoO): Relevance of existing rules of origin to 3DP

– Customs revenues: Customs revenues and the moratorium on electronic transmissions

This list is not exhaustive. Other areas also deserve further analysis, including the effect of data regulations on market access of CAD files as a form of electronic transmissions. Data localization requirements might add friction costs when transmitting CAD files across borders to be printed in another country. Moreover, the design of the CAD files itself might imply multiple cross-border data flows if the files are the result of collaborative creation using a cloud-based solution (Rentzhog, 2016).

Box 3: Will 3DP slow down or accelerate trade?

Slow down:

The International Trade Analysis team at ING (Leering, 2017) estimated that one-quarter of world trade could be decimated by 2060 if half of manufacturing is displaced by 3DP.

McKinsey Global Institute (Lund, S., et al., 2019) estimated that 3DP will reduce physical trade by 1-2% by 2030.

Accelerate:

A recent World Bank study (Freund, Mulabdic & Ruta, 2019) found that trade in hearing aids increased 58% when 3DP started dominating hearing aid production. By analysing 35 products that are partially 3D-printed, the study found positive and significant effects on trade. It also pointed out that product weight and its effect on logistics costs will be drivers for shifting production close to consumption.

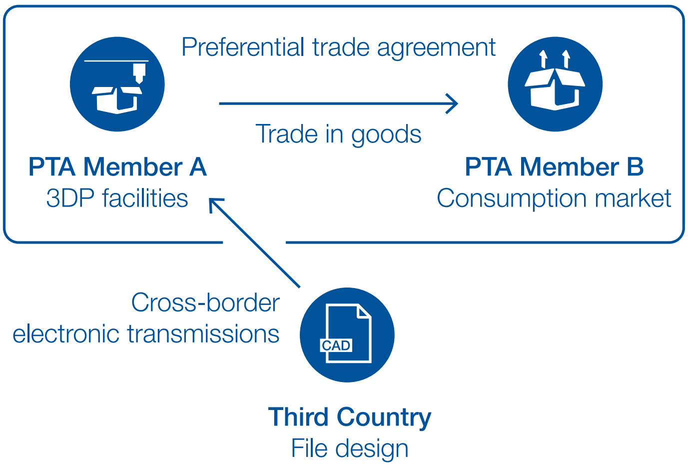
Classification: Are digital products such as 3DP design files categorized as goods or services? The answer to this will define which multilateral trade agreement will apply to 3DP files – the General Agreement on Tariffs and Trade (GATT) if they are categorized as "goods", or the General Agreement on Trade in Services (GATS) if they are designated as "services". The two agreements are mutually exclusive and, hence, under current trade rules, a product cannot be considered to be a combination of a good and a service. GATT imposes most-favoured-nation (MFN) and national treatment (NT) obligations horizontally, while the GATS structure is more flexible, and market access and NT obligations vary depending on specific commitments of countries in their schedules. Therefore, commitments vary significantly based on whether a product is classified as a good or a service. Regions and countries have different interpretations. An example is the case between the European Commission and the United States (Fleuter, 2016). Recent large preferential trade agreements (PTAs) with ambitious digital trade chapters, such as the Comprehensive and Progressive Agreement for Trans-Pacific Partnership and the United States-Mexico-Canada Agreement, do not enter this discussion either. These uncertainties on how to classify digital products have practical implications for businesses, as they raise questions on how countries would treat imports of digital products.

Rules of Origin (RoO): The printing of 3DP objects requires the design of the CAD files, the printing instructions (known as G-code) and the actual printing of the object. In trade policy, RoO are defined in such a way as to determine where the last "substantial transformation" took place. This is relevant for determining whether a product originated from a member of a PTA and thus qualifies for a reduced tariff or no tariff. This is an important feature of trade policy as current production patterns are spread over complex global supply chains. The question then arises of where the last substantial transformation takes place for 3D-printed products: is it at the design stage or at the time of printing?

This is more of an issue for RoO that are based on a change of product classification under the Harmonized Commodity Description and Coding Systems (HS Code). Virtually any 3D-printed product would qualify for a change in product classification, as it would have been transformed from a filament or other raw material to a different product, thus following a different classification under the HS Code. As such, any product feasible of being 3D-printed could qualify for a reduced tariff or no tariff under a PTA if its RoO were based solely on a change in product classification.

Another layer of complexity arises if a product designed in a country that is not part of a PTA qualifies for preferential access when printing takes place in a PTA member country (Figure 6). The question remains: is the click of a button triggering the printing equivalent to traditional production processes, from a value-addition perspective? Is the value addition derived from the printing enough to consider the product as originating in that country, and thus eligible for preferential market access? Or does most of the value come from the design of the 3DP file? If so, consideration should be given to whether RoO based on a change in product classification might underestimate the value addition embedded in the design of the file, while possibly overestimating the value addition coming from the 3DP process itself.

Figure 6: Does the last substantial transformation happen where 3DP takes place?



Source: World Economic Forum and Mitsubishi Chemical Holdings Corporation

Is the click of a button equivalent to following traditional production processes, from a value-addition perspective? Where does "substantial transformation" take place through the lens of 3DP? Is it in the market where the CAD file is designed? Or where the CAD file is printed at the 3DP facilities? This question is relevant as certain rules of origin based on a change of product classification under the HS code might give preferential access to products that were sophisticatedly designed in third countries and only printed in a member of a preferential trade agreement.

Customs revenues: For the cross-border flow of 3DP design files, customs revenue questions could be connected to the future of the moratorium on electronic transmissions. In 1998, WTO members adopted a Declaration on Global Electronic Commerce, which included a commitment not to impose customs duties on electronic transmissions for the following two years, known as the "moratorium". The moratorium on duties for e-transmissions has been extended ever since in subsequent Ministerial Conferences of the WTO. While some countries value the moratorium as an instrument to facilitate online and even offline trade, others consider the opportunity cost in terms of perceived revenue loss and argue for the need to promote their infant digital industries (see the Appendix: "Moratorium on electronic transmissions").

Another consideration is that the eventual imposition of customs duties on electronic transmissions would imply having the same level of control over digital flows as over trade in goods. Thus, technology solutions will be needed to track 3DP design files and other e-transmissions crossing borders. This leads to another debate on, if feasible, whether all countries might be able to acquire the technology base to monitor digital flows. Such processes could also add new levels of friction costs for digital trade as experienced by goods traders clearing borders.

What actions could business and policy-makers take for trade and customs?

Business:
Develop standards for 3DP files and create secure, traceable digital transmission methods

Policy-makers:
Collect and publish statistics on 3DP; explore the relevance of trade instruments from a 3DP perspective

Adjust to shifts in global supply chains

In a scenario of wide adoption of 3DP, global supply chains could face many challenges. This section explores the potential positive and negative effects while operating with certain assumptions about the trajectory of the technology and global supply chains.

With 3DP as a core enabler, advances in cloud computing, AI and IoT could promote decentralized manufacturing. Supply chains will be affected under 3DP-enabled decentralized manufacturing in several scenarios:

- Linear value chains may be replaced by agile networks of on-demand FabLabs; as these actions scale up, supply chains could undergo a dramatic change – there would be a much higher flow of 3DP input materials than intermediary inputs and finished goods, as previously discussed.
- The digital flow of designs would also increase.
- Because of the efficient use of materials in 3DP due to the additive method, lower amounts of raw materials would be needed.
- The weight of finished parts would go down as hollowed designs are adopted.
- Keeping spare parts in inventory could become a thing of the past, as parts could be printed on demand – see, for example, the case of Mercedes Benz (Watkin, 2018), where automobile parts for some older model vehicles are printed on demand instead of being kept in inventory.
- If mass customization takes off, perhaps fuelled initially by postponement strategies such as name engraving, production might move closer to consumption, and offshoring may be less of a cost advantage (though Box 2: "How is reshoring playing out today?" provides another perspective).
- There could also be fewer returns and less material waste because of better matching of products to customer needs.

The extent of the effect on freight traffic would depend on the extent of 3DP adoption in mainstream manufacturing. Though some projections place the impact on air cargo volume to be only 2-4% (Air Cargo News, 2018), such estimates are based on the limited use of 3DP, within niche areas. As shipments move from components and semi-finished goods to 3DP input materials, transportation could be expected to become more efficient because of the relative ease of shipping these. Logistics service providers might see a significant shift in the physical product flows they manage and could consider building competencies, such as 3DP as a service.

Assuming large-scale adoption of 3DP, supply chain networks will need to undergo fundamental shifts with the elimination of some supply nodes. Consolidation and reduction in freight traffic could lead to regional economic losses in countries that benefit from low-cost manufacturing labour or rely heavily on traffic through their ports. But it could generate other opportunities yet to be fully understood, and potentially associated with complementary services to 3DP.

What actions could business and policy-makers take for global supply chains?

Business:
Ask these questions about the supply chain and 3DP: What areas in my supply chain and operations are potentially affected by 3DP? How do I protect my business and take advantage of the opportunities that will come my way? What needs to change across my design-buy-make-move-fulfil supply chain to help stay ahead of the game? What is the business case and what should my supply chain and operations transformation path look like?

Policy-makers:
Help provide regulatory support for the growth of 3DP in regions affected by revenue loss due to change in supply chains

Ensure legality and safety in the 3DP-rich world

In recent news, 3D-printed guns (All3DP.com, 2019) have garnered much attention, leading to debates on whether 3D-printed guns should be banned. The ease with which 3D digital models can be downloaded and printed in the safety and anonymity of one's home is starting to create concern among lawmakers. Further, the speed with which digital information can be distributed on a global scale has raised fears of large-scale violation of copyrighted 3DP parts. A well-known example was Napster; created in 1999 for sharing digital music files, it grew to 80 million registered users. Following a lawsuit by the Recording Industry Association of America, it was shut down in 2001. But the possibility of rapid, illegal global distribution of digital content had been demonstrated, and it could happen again for 3DP.

3D scanners, which can make digital copies of physical product shapes, are advancing rapidly, benefiting from better sensors and AI algorithms. With a high-performance 3D scanner, high-fidelity copies of physical products can be made and printed using a 3D printer. This could result in the proliferation of illegal copies of brand-name products.

In addition, 3D-printed parts may fail during use and cause harm. In these situations, who is responsible? The designer, the platform where the file is available, the printer manufacturer, the raw material manufacturer, or the one who printed the part? Illicit, poor-quality raw materials may also result in failures and harm. Finally, when mission-critical components (e.g. for aircraft) are 3D-printed, these risks will be compounded by cybersecurity threats.

Box 4: How to protect 3DP designs and finished goods

– Protect design files using the Digital Millennium Copyright Act (as design patents are weak)

– Use software to limit access to design files

– Secure trademark for recognizable designs

– Keep raw material formulas and production methods as trade secrets

– Rely on goodwill and brand strength rather than IP protection

– Follow industry-standard cybersecurity protection methods

– Promote global regulatory schemes that provide for unique "markings" on 3DP products

To address some of these issues, the current legal system offers various instruments (Box 4). In the trade realm, the WTO Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) applies to both physical and digital products, and is thus applicable to works produced with 3DP. While TRIPS provides the minimum standard of protection, national legislation prescribes the protection in each country.

At the national level, the three major forms of IP protection, with limited enforceability, are copyright, patent and trademark. While 3D design files can be protected by copyright, circumventing copyright may be relatively easy by making small changes to the file. Copyright does not offer protection for functional aspects of 3D-printed products, as it only protects the expression of the original creation.

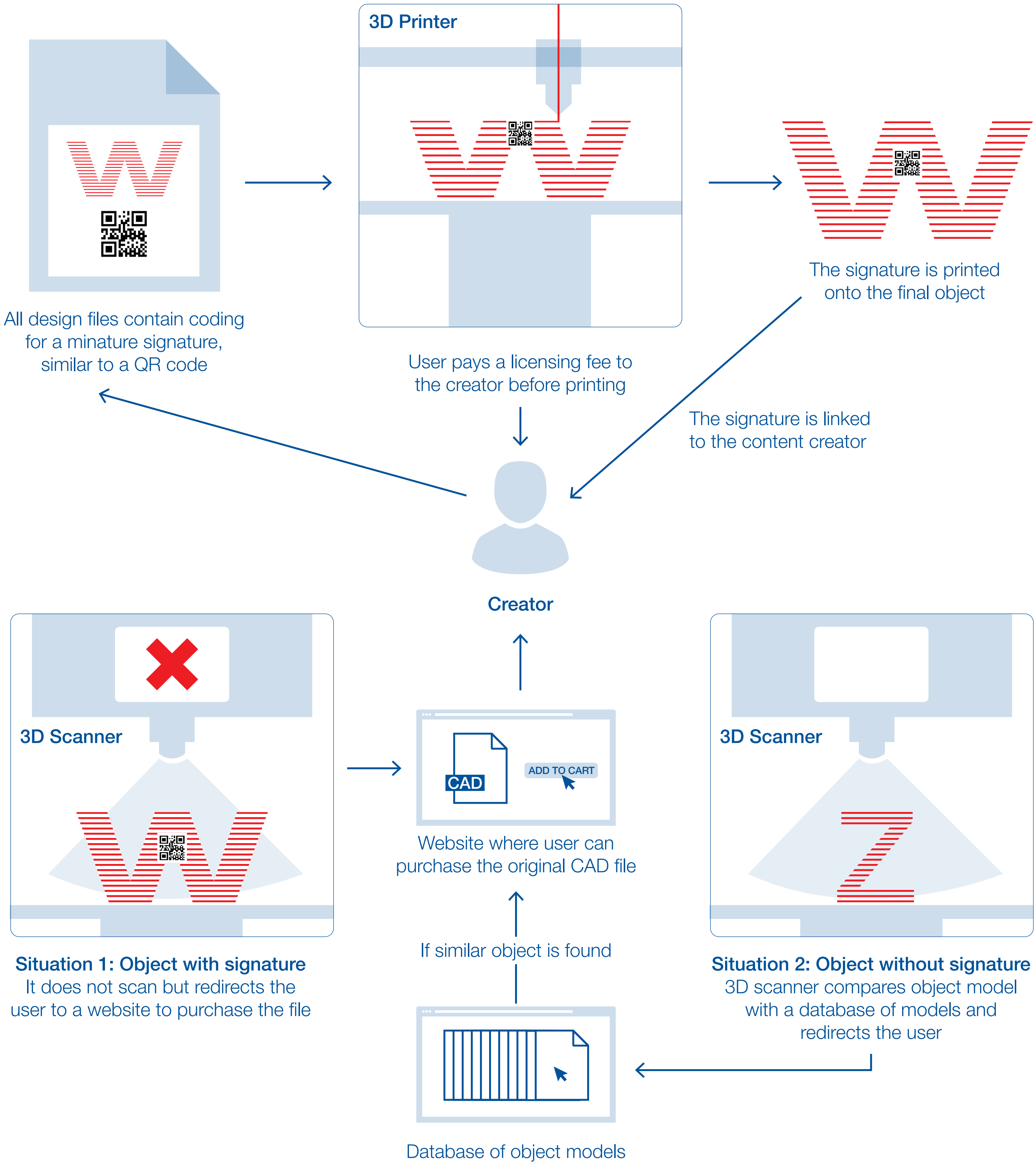
Patent law, which protects only "new and useful" innovations, is likely to exclude 3DP products that contain only a new design as opposed to embodying a novel, useful idea. Patent infringement might be easier to identify as only the patent holder (or a licensed party) has the right to exploit the idea. Design patents offer protection that is limited to ornamental design features of an object, as opposed to useful aspects of that object's design. Thus, they might be relatively easy to circumvent with 3DP (Rentzhog, 2016).

Trademark protection for 3DP products is the same as for any other product. Specifically, trademark rights protect the goodwill of a company by prohibiting another from copying a design or mark that consumers associate with that company. TRIPS allows for non-commercial use of trademarks, which means that printing for personal use could be permitted without creating an infringement (Rentzhog, 2016).

Trade secret serves as an additional type of protection for certain types of IP that can be kept secret. Because of the digital nature of 3DP, however, it will generally be difficult to keep commercial 3DP designs a secret, rendering trade secret a poor form of protection for finished goods, though it might offer protection for raw materials.

In response to the limited IP protection for software and similar products (e.g. CAD files), developers have turned to encryption and password protection to prevent unauthorized copies. Determined hackers, however, have found ways to circumvent encryption and password protections in the past. As a result, the World Intellectual Property Organization

Figure 7: Example of a global regulatory scheme



Source: World Economic Forum and Mitsubishi Chemical Holdings Corporation, with contributions from Latham & Watkins has included an anti-circumvention provision in its Internet Treaties, which have been implemented in various countries' legislations. For example, the United States enacted the Digital Millennium Copyright Act (DMCA) to outlaw unauthorized hacking or circumvention of such encryption and password protection. The significant criminal and civil penalties under the DMCA deter some from circumventing copy protection. Similarly, the European Union implemented technological protection measures in the Information Society Directive. Australia has also included anti-circumvention protection in Section 116 of its Copyright Act.

Moreover, several start-ups around the world are developing technical solutions, such as those based on blockchain, to offer secure methods of transferring 3D designs. These approaches may be vital to the long-term success of 3DP. To be truly effective, a global regulatory scheme, such as the one shown in Figure 7, may be needed.

Additional technologies may be used in the scheme, including blockchain for securing and tracking transactions and product origin information (Truton, Vitale & Killmeyer, 2016) or privacy-preserving computation techniques (Big Data UN Global Working Group, 2019), to allow creators to keep designs private while still enabling their use.

What actions could business and policy-makers take for legality and safety?

Business:
Use software to limit access to design files; keep raw material formulas as trade secrets; use IP protection forms available to 3DP (see also Box 4)

Policy-makers:
Adjust IP law to address 3DP specificities; develop global regulatory schemes that facilitate the tracking of CAD files to remunerate creators

Promote environmental sustainability

Invented in the 20th century, plastic was designed for longevity and ease of production. More recently, acute awareness of the impact of plastic waste on the environment has been increasing. Sustainability has become part of global dialogues, as exemplified by the United Nations Sustainable Development Goals (Sustainable Development Goals Knowledge Platform, n.d.).

If 3DP becomes available at the household level, plastic waste may increase as prosumers experiment with multiple versions of a part until satisfied, discarding the unsatisfactory ones in the process. On the flip side, since products can be customized to meet individual requirements, "reverse flows" (i.e. products being returned because they do not meet customer needs or due to excess stock) could be significantly reduced. Opportunities for sustainability could be enhanced if 3DP were to allow for the ability to "melt" a printed part into raw material ready for reprocessing, where the future of making objects could be like moulding clay or play dough. Some novel experiments are looking at using locally sourced, recycled plastics in 3DP (Garmulewicz, et al., 2016).

Being new relative to traditional manufacturing, 3DP offers an opportunity to redesign raw materials and finished products to meet sustainability needs. Raw materials can be designed to be recyclable, which enables innovative, sustainable material design. Products can also be designed to use less material, using structures that are difficult to make with traditional manufacturing, such as honeycomb or hollow structures. Generative design, an AI-enabled method for designing novel structures to meet functionality and strength-to-weight ratio requirements, can consider sustainability and recyclability requirements as well (Figure 8).

Further, 3DP manufacturing wastes less material than traditional manufacturing because of the additive approach. It also reduces the amount of freight movement (as the need to move intermediary inputs decreases with 3DP) and the need for large facilities and processes. These result in reduced CO_2 emissions and a lower impact on the environment (McKinnon, 2018). Although beneficial in many ways described thus far, this technology must be guided by strong environmentally focused policies to have net positive environmental benefits (Faludi, et al., 2017).

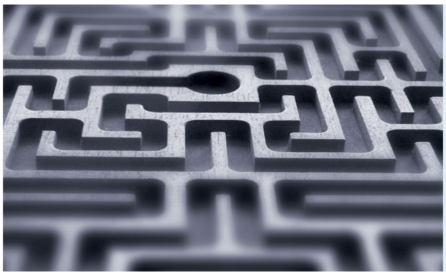
What actions could business and policy-makers take for the environment and sustainability?

Business:
Be mindful of plastic waste at initial stages of prototyping; optimize design to use the least amount of material

Policy-makers:
Encourage the use of materials that promote reuse and recycling; drive environmentally focused policies for 3DP

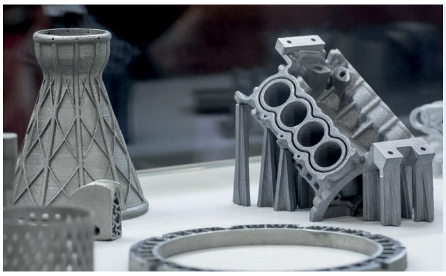
Figure 8: Opportunity to improve sustainability through generative design of 3D-printed products

- Product functional constraints
- Form & performance constraints
- Sustainability constraints
- Material choices

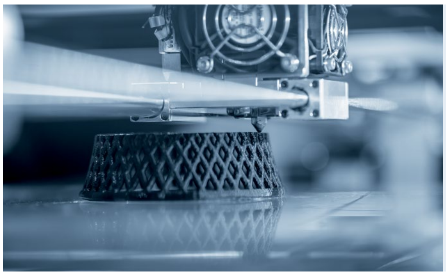


Explore
An AI-based system can explore a large number of design options, and suggest the ones that best meet requirements

Generative design allows fast, automated exploration of the design space to create never-before-possible objects, by taking into consideration the unique capabilities of 3D printers, material choices, constraints on form and function, and even sustainability constraints.



Optimize
The automated system does the hard work, optimizing for requirements and constraints, allowing the human designer to focus on innovation



Make
A 3D printer can produce objects previously impossible to make because of the layer-by-layer build-up of the object

Products with:

- Desired functionality
- Novel forms
- High performance
- Recyclable
- Sustainable

Source: World Economic Forum and Mitsubishi Chemical Holdings Corporation

Next steps

3DP is a promising new technology that brings much hope and has brought a lot of hype in the past. The future is full of possibilities; these lead to intended and unintended consequences in a variety of domains. The overview of the state of 3DP in this White Paper includes the analysis of some of the consequences and potential approaches to address them, as well as leading indicators that can be used to monitor them.

If 3DP becomes more widely adopted across industries and countries, some suggested actions and next steps for several constituents to act upon are:

- Business leaders can prepare themselves for a 3DP world by: (1) adopting the right strategies to include 3DP in their businesses; (2) incorporating leading indicators in their annual operating plan processes; and (3) collaborating with regulators on regulations that benefit everyone.

- Policy-makers can prepare themselves for a 3DP world by: (1) developing regional and national strategies for encouraging healthy ecosystems for 3DP; (2) adjusting existing regulations/laws and/or developing new ones to prepare for potential unintended consequences; and (3) incorporating leading indicators in periodic planning processes for trade, customs, IP regimes and cybersecurity, among other areas.

- Academic experts can develop economic models for the adoption of 3DP to provide quantitative guidance to decision-makers.

The World Economic Forum is prepared to work with a diverse group of stakeholders to facilitate the development and implementation of practical 3DP policies. These include exploring with industries to design future-proof standards for 3DP; with international organizations to develop guidelines on cross-border challenges; or with a government to draft a national strategy on 3DP. They all have the goal to maximize the benefits and mitigate unintended consequences of 3DP technology in the Fourth Industrial Revolution.

Appendix: Moratorium on electronic transmissions

Debate continues regarding the moratorium on electronic transmissions in recent years. On the one hand, some World Trade Organization (WTO) members propose making the moratorium a permanent commitment in the multilateral trading system, arguing that it facilitates digital and offline trade. They claim further certainty is needed rather than leaving the option of its renewal open at each WTO Ministerial Conference every two years. Some members have made it permanent in preferential trade agreements (PTAs) among themselves. On the other hand, other members argue for the need to explore the option of applying customs duties on electronic transmissions to promote their infant digital industries or to recuperate a perceived loss of revenue.

Broad disagreement over which trade flows may be digitized in the future and how to measure the perceived revenue loss, whether based on bound or applied tariffs, has led to a wide range of estimates.

The United Nations Conference on Trade and Development (UNCTAD) has estimated the potential tariff revenue loss derived from the moratorium by income level. According to its estimates, developing countries would be losing customs revenues of $10 billion annually, while estimates for least developed countries and African countries would be at $1.5 billion and $ 2.6 billion, respectively, when using bound tariffs for the calculations. Estimates vary when using the average most-favoured-nation applied rate, where the potential tariff revenue loss on electronic transmissions would amount to $5.1 billion for developing countries and to $289 million for high-income countries (Banga, 2019).

A European Centre for International Political Economy (ECIPE) study argues that the loss of revenue from customs duties would be minimal in comparison to this bigger effect in the overall economy. ECIPE estimates that it would be counterproductive to impose tariffs on electronic transmissions. Higher prices and less consumption would result in a slowdown of growth in gross domestic product (GDP) and reduced overall tax revenues. Departing from UNCTAD estimates in 2017, ECIPE projects that India would lose 49 times more in GDP than it would generate in duty collection via digital means, when considering a scenario in which tariffs imposed would give way to reciprocal tariffs. For Indonesia, the loss in GDP would be 160 times more than it could collect in tariffs, while the relation for South Africa and China would be 25 and 7 times more, respectively (Lee-Makiyama & Narayanan, 2019).

A recent study by the Organisation for Economic Co-operation and Development (OECD) estimates that only 1.2% of total trade is digitizable goods, and it estimates this will likely remain low while considering the effect of new emerging technologies such as 3DP in the short term. According to this study, the potential foregone customs revenue would be between 0.08% and 0.23% for developing countries. The OECD goes a step further to assess the gains derived from the current application of the moratorium, by including the benefits associated with tariff-free electronic transmissions in the analysis. The analysis shows that if today all digitizable goods were transmitted electronically, consumer welfare globally would increase by $940 million, offsetting costs associated with revenue loss by $73 billion (Gonzalez, 2019).

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