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3D Printing – A New Industrial Revolution

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Abstract *Along the history, the people`s inquisitive minds invented technologies that changed the economic landscape in ways difficult to imagine for previous generations. Among the so-called "disruptive technologies" that marked the progress of humanity: the printing press, the mechanization of the textile industry, electricity, the assembly line, nuclear energy, programmable computer, the digitalization of production, namely additive manufacturing or 3D printing seems to represent a new economic paradigm, changing the output pattern fundamentally. Our paper aims at unveiling the main features (SWOT analysis) and economic implications of this new disruptive technology, identifying the main players and sectors based on the available literature and statistical data.*

Keywords:
3D printing, disruptive technology, industrial revolution, industrial relocation

JEL Codes:
F20, L16, L64, O14, O33, O34

1. Introduction

Disruptive technology changes the way a business operates by introducing new, better, more facile ways of production or services delivery. Before the industrial revolution in England (18th century), the tasks performed in just a cotton mill were allocated among hundreds of weaver`s cottages. Imagine the surprise Adam Smith would have had if somebody had told him that a pin can be printed, instead of being produced within the framework of the "division of labour." Electricity and electrical devices brought light into our lives and paved the way to technologies our forefathers could not imagine. The Internet changed the communication pattern among people around the globe completely, enabling a real-time exchange of information and ideas opening the minds of individuals secluded by cultural, educational and geographical barriers.

"Technology advancement is the driving force of industrial economies. The birth and death of technologies and waves of product cycles are common features of a modern economy. Industry competition for increasing market share is largely driven by technology rather than price. The essence of industrial revolution is opening up new resources, not just an efficient utilization of existing resources" (Chen, 2010).

Bower and Christensen (1995) argue that "disruptive technologies introduce a very different package of attributes from the one mainstream customers historically value, and they often perform far worse along one or two dimensions that are particularly important to those customers. As a rule, mainstream customers are unwilling to use a disruptive product in applications they know and understand. At first, then, disruptive technologies tend to be used and valued only in new markets or new applications; in fact, they generally make possible the emergence of new markets." Tellis (2006) agrees that "the disruptive technology initially underperforms the dominant on dimensions the mainstream market demands, but with steady improvements it meets or exceeds those demands."

The WIPO experts (2015) argue that the beginning of 3D printing date back to the 19th century to photosculpture and topography works, but the first attempt to create three-dimensional objects using computers and specialized programs was in the 1960s. The main research was conducted by the Battelle Memorial Institute in Columbus, Ohio and Wyn Kelly Swainson in Berkeley, California. "The first functional 3D printing technique was reported by a Japanese scientist, Hideo Kodama, at the Nagoya Municipal Industrial Research Institute," (WIPO, 2015).

According to Weller *et al.* (2015), the additive manufacturing technology is used since the 1980s, in the early stages of implementation being limited to the production of prototypes. "The technology's primary goal was to offer an affordable and fast way to receive tangible feedback during the product development process; prototypes were usually not functional."

Wittbrodt *et al.* (2013) emphasize that the 3D printers are "self-replicating rapid prototypers (RepRaps) that can manufacture approximately half of their parts from sequentially fused deposition of polymer feedstocks. RepRaps have been demonstrated for conventional prototyping and engineering, customizing scientific

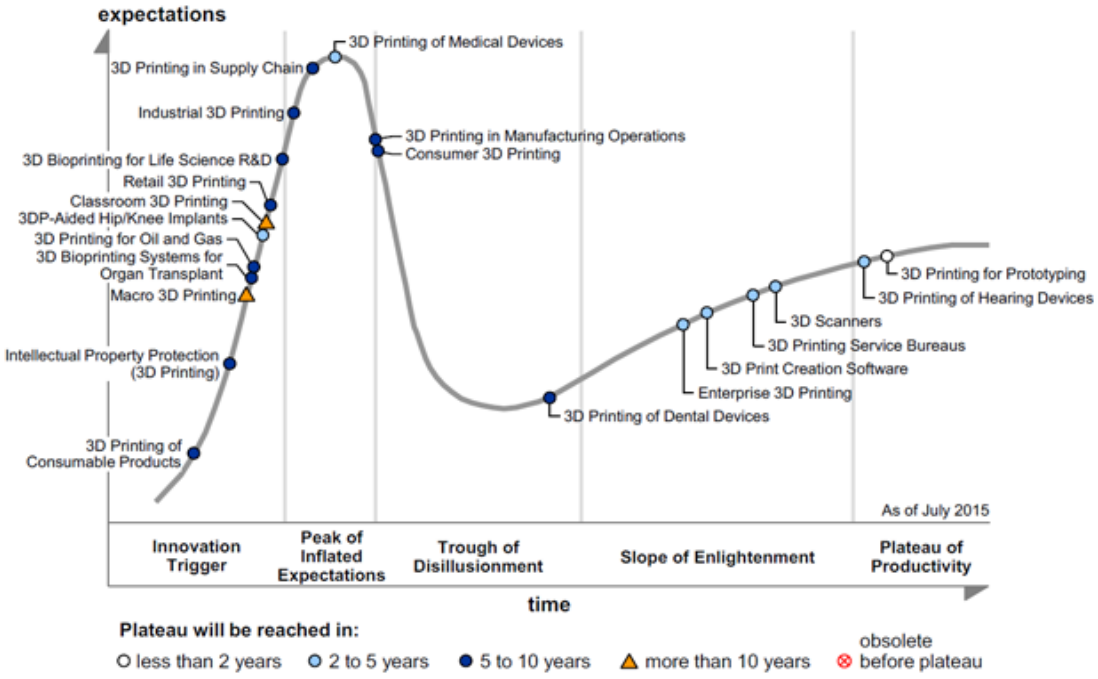
equipment, and appropriate technology-related manufacturing for sustainable development."
Feixiang *et al.* (2016) explain that "3D printing adopts an additive manufacturing process whereby products are built on a layer-by-layer basis, through a series of cross-sectional slices. All 3D printers use 3D-CAD software that ensures thousands of cross-sections of each product to determine exactly how each layer is to be constructed." According to the specialists from "The Economist" (2015) the most common method of printing metal structures is selective laser melting (spreading a layer of metallic powder onto a base and then fusing the particles together in the shape required by the design, all the process being controlled by a computer software.
In the 2015 World Intellectual Property Report (WIPO, 2015) the experts of the organization centralize some of the breakthrough innovations of the last two centuries regarding their equivalent impact on the economy.

Table 1. Breakthrough innovations

Historical innovations	Current innovations
Airplanes – from hobbyists gliding in the 19th century to a reliable mode of transportation in the first half of the 20th century	3D printing – the creation of 3D objects through successive layering of material, aided by digital technology
Antibiotics – from the discovery of sulfa drugs in the 1930s to the birth of the modern pharmaceutical industry	Nanotechnology –technology at the scale of one-billionth of a meter, with applications in electronics, health, materials, and other fields
Semiconductors – from amplifying radio waves for better communication in the early 20th century to ever more potent computer chips driving the ICT revolution	Robotics – from the first robots spurring industrial automation to today's autonomous machines with artificial intelligence

Source: World Intellectual Property Organization, 2015

The WIPO experts consider that 3D printing development could have the same impact on manufacturing industry as the airplanes had on transportation industry in the last century.



Source: Gartner, 2015

Figure 1. Hype Cycle for 3D Printing

Gartner (2015) makes predictions about the evolution of 3D printing and its applications. According to their study (Figure 1), in the next two years we will witness an increase in the 3D printing for prototyping; in 2 to 5 years the expansion will include additive manufacturing of hip/knee implants, prostheses, casts, screws, printing parts for medical equipment, enterprise 3D printing,

print creation software, 3D printing Bureaus, 3D hearing devices and 3D Scanners;
In the next 5 to 10 years the developments will include 3D printing of consumable products, intellectual property protection of the field, 3D bioprinting of organs for transplants (the first transplant of a 3D printed liver is expected by 2024, as per World Economic Forum - 2015), oil and gas printing, industrial 3D printing, printing of dental devices (orthodontic braces, crowns, dental implants), consumer 3D printing etc.; in a time horizon of ten years the Gartner analysts envisaged macro 3D printing and classroom 3D printing. Dumitrescu (2015) underlines that the additive manufacturing industry will reach a turnover of over $8 billion by 2020, the leading regions in this field being the Americas, Europe, and Asia, China aiming to promote 3D printing as a mean to produce economic goods. McKinsey GLOBAL Institute research suggests that 3D printing could have an economic impact of $550 billion a year by 2025 (McKinsey, 2013).
A report published by Hudson Valley 3D Printing shows that the sales of 3D printing products and services could exceed $6.5 billion by 2019 since the number of commercial additive manufacturing devices increased 6,500% from 2008 to 2013.
According to the WIPO experts (2015), the additive manufacturing will generate revenues of $20 billion by 2020, the financial impact of the new industry being estimated at around $230-550 billion per year by 2025 ($100-200 billion for direct manufacturing, $30-50 billion for tools and moulds and $100-300 billion on consumer) Forbes (2015).

Table 2. Market estimates for 3D printing

Market	Estimated potential	Source
Global 3D printing industry (associated technologies, products, and services)	$10.8 billion by 2021	Wohlers Associates, 2013
Global 3D printing industry (associated technologies, products, and services)	$4,0 billion by 2025	Research and Markets, 2013
3D printing materials market (including plastics, metals, ceramics, others)	CAGR[1] 19.9% until 2018	RnR Market Research, 2014
3D printing for medical application	$965.5 million by 2019, CARG 15.4%	Transparency Market Research
AM market	$7 billion by 2020 on 18% CAGR	Paul Coster of JP Morgan
Bull market scenario	$21,3 billion by 2020, on 34% CAGR	Ben Uglow of Morgan Stanley
3D Industry	$10,8 billion in worldwide revenue by 2021	Wohlers Report
3D Printing global	$13,4 billion by 2018, attaining a 103.1% CAGR	Gartner
3D Printing global	$8,6 billion in 2020, attaining a CAGR of 20,6%	Allied Market Research
3D printing global	$8,3 billion by 2023	Siemens
3D printing global	$8,6 billion by 2020, attaining a CAGR of 20,6%	Business Wire, 2014

Source: WIPO (2015), Bechtold et al. (2015), Forbes (2015)

In Table 2, we notice that the estimated potential of additive manufacturing varies from $4 billion to $13.4 billion in the next five to ten years. As the experts of Hudson Valley Economic Development Corporation underlined if only 10% of the global manufacturers begin employing 3D technology we will eventually see a $1 trillion industry in the future.

[1] Compound Annual Growth Rate

Table 3. The SWOT analysis of additive manufacturing (3D Printing)

Strengths	Weakness
Cost reduction for tailored small batches Cost-free change of product design Creation of prototypes without tooling and getting quick feedback from the customers. Reduction in the design-to-manufacturing cycle Eliminates the need of screwing and welding different parts of an end product Pieces that used to be moulded separately and then assembled can now be produced as one piece in a single run (a nozzle that used to be assembled from 20 separately cast parts can be fabricated in one piece) Uses new, lighter, stronger and more durable materials Saving construction time Cutting expenses Improving efficiency Enables more flexible designs (complex shapes and structures) Slashing development time for companies Eliminating tooling costs Eliminating the waste that accrues in traditional manufacturing Environmental benefits from reduced transportation requirements Helps companies maintain and reinforce control of the entire value chain Increased flexibility in manufacturing	The size of the 3D printers currently available (the printed objects need to fit inside the machine) Suitable raw material is considerably more expensive than many raw materials used in traditional manufacturing The cost of future materials The speed of printing The cost of 3D printers (industrial printers cost ranges from $95,370 to $15,000 - and home versions around $1,000) At present, 3D printers can only make parts, not whole products unless the product is made 100% of the same material For thousands or millions of parts injection moulding is cheaper 75 percent of all patents in the field of 3D printing have been registered by a handful of countries: Japan, USA, Germany, Britain, South Korea, China Additive manufacturing is a slow process, requiring hours or days to finish the printed object Low expertise in designing products for AM Lack of channel partner assistance has been restraining the growth of the market
Opportunities	**Threats**
Rising demand for designers, engineers and IT specialists Home relocation of offshore production Printing infrastructure items on site for space programs (landing pads on Moon and Mars) Producing simple lab apparatus Using crowdsourced brainpower to replace or complete companies` R&D activities Producing complex parts in remote countries with lower input costs for electricity and labour Development of universal printing standards Lower tooling costs Testing low volumes of goods Growth in open-source files to print objects Birth of a new industry supplying printing materials Transportation cost savings Supplying small production runs so entrepreneurs can scale up to mass-manufacturing without needing outside investment	Fear of change at governmental level Governmental protection of the existing industries and companies Consumer regulations Trade barriers Patents Production control Printing firearms and other military equipment Job losses in disrupted industry Potential that any innovation can be instantly copied Brand and product quality Uncontrolled or unregulated production of body parts, medical equipment or food Impact on agriculture from printing food

Source: Authors` selection from: Cohen et al. (2014); The Economist (2012, 2015); World Economic Forum (2015); D`Aveni (2015).

2. The Advantages of Additive Manufacturing

The lack of industrial waste is one of the most significant benefits of this technology. We can say that 3D printing is a “green” process because the printing material is added layer by layer, in the exact quantity as required by the production specification, under computerized control.

Through this technology, identical objects can be printed anywhere in the world since the producers need only three things, a printer, a digital file that can be sent fast in any corner of the world and the printing material.

Additive manufacturing can produce objects regardless the shape, limitation that currently exist in various industries. With this ability, producers can switch from a complex product to a simpler one without having any additional cost or waste of time, and raw materials.

Table 4. Top 10 patent applicants in 3D printing

Rank	Applicant	Origin	First fillings
1	3D Systems	USA	200
2	Stratasys	USA	164
3	Siemens	Germany	145
4	General Electric	USA	131
5	Mitsubishi	Japan	127
6	Hitachi	Japan	117
7	MTU Aero Engines	Germany	104
8	Toshiba	Japan	103
9	EOS	Germany	102
10	United Technologies	USA	101

Source: World Intellectual Property Organization, 2015

The Table 4 emphasizes that in the field of 3D printing, the American companies are leading the way in the top of patent applications (596), followed by Germany (351) and Japan (347).
According to WIPO (2015) "In early 1980s Japanese applicants were prolific in filing for patents on their 3D printing inventions, but by the 2000s they had been overtaken by US applications. By 2010, Chinese applicants were filing for more 3D printing applications – almost as many as the Japanese and US applicants combined" (Table 5).

Table 5. Top ten university and Pro-patent applicants, since 1995

University name	Country	Number of first patent filings
Fraunhofer Society	Germany	89
Chinese Academy of Sciences	China	79
Huazhong University of Science & Technology	China	46
MIT	USA	37
Xi'an Jiaotong University	China	34
University of Southern California	USA	31
South China University of Technology	China	27
Harbin Institute of Technology	China	24
TNO	Netherlands	24
Beijing University of Technology	China	17

Source: WIPO, 2015

Gartner (2015) predicts that the worldwide shipments of 3D printers will reach almost 500,000 units in 2016, meaning that it will grow by 103% from the predicted 244,533 units in 2015 and "only" 108,151 units in 2014. This rapid increase in 3D printing units continues the transformation of the market from a niche market to an international one. This growth is determined, by the decrease in the price of the 3D printing devices for home use ($1.000 to $5000). However, it is important to understand that these printers have limited functionality printing small, low-quality objects, taking a longer time than the industrial ones. On the other hand, the companies lead the additive manufacturing market, operating very expensive printers that use high quality and pricey raw materials, leading the market (almost 90% of all 3D printers, 95% of the volume of printed objects and nearly 99% by economic value according to Deloitte - 2015).

Table 6. Top 5 Vendor 3D Printer Market Share by Units Volumes, Global Desktop/Home Printers, YTD 2015 (Q1-Q3)

2015 Rank	Company	Brand	Units	Global Share (%)
1	XYZ printing (Taiwan)	Da Vinci	28,300	17%
2	3D Systems (USA)	Cube/Cubify	20,290	12%
3	Stratasys (USA)	MakerBot	15,426	9%
4	Ultimaker (the Netherlands)	Ultimaker	14,734	9%
5	M3D (USA)	The Micro	14,436	9%

Source: CONTEXT 3D Research Update 2016

The American companies in the top 5 (Table 6) have a global market share of 30%, followed by the Taiwanese company XYZ printing that is the world leader in home 3D printers, having alone 17% of the global market share. Ultimaker of the Netherlands has a 9% global market share.

Table 7. Top 5 Vendor 3D Printer Market Share by Units Volumes, Global Enterprise/Professional Printers, YTD 2015 (Q1-Q3)

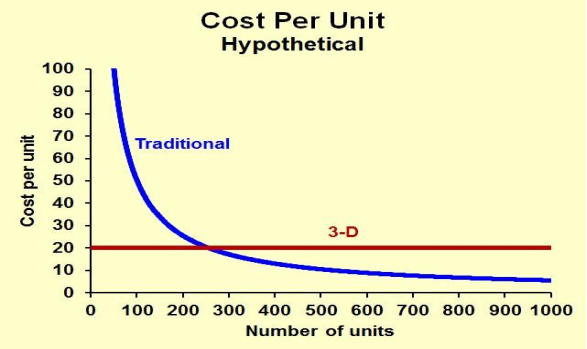
2015 Rank	Company	Revenues from units sold ($)	Global Share (%)
1	Stratasys (USA)	333,783	40
2	3D Systems (USA)	138,201	17
3	EOS (Germany)	137,530	17
4	SLM Solutions (Germany)	28,479	3
5	Arcam (Sweden)	27,746	3

Source: CONTEXT 3D Research Update 2016

Regarding professional 3D printers (Table 7) the American companies have a global market share of over 57%, followed by the German companies (20%) and Arcam of Sweden (3%).
Stratasys, the largest 3D printing company in the world, has seen a huge 60% year-on-year growth in demand for its 3D printing services.

3. Is 3D printing a real revolution?

To answer the question, we can have a look at the internet revolution. In the beginning, when the internet was being developed, most of the people did not realize its potential in the way the businesses did. As the new technologies developed and the markets started using and promoting the new hi-tech solutions, people became more aware of its potential and started using the World Wide Web. Today, the internet is used in almost every field of social and economic life, contributing to the development of many industries.
Considering that the internet revolution required between 15 to 20 years getting close to its potential, the 3D printing revolution, as the Gartner (2015) analysts forecasted, will take at least ten years to reach its fine tune, and get to the next level of macro additive manufacturing and classroom 3D printing, for educational purposes. However, today, due to the internet, people access information quicker, speeding up, thus the implementation process of additive manufacturing and other cutting-edge technologies. That explains why the 3D printing forecasts are so optimistic. We just need to have patience and see the snowball rolling in the right direction because the revolution is happening and will represent a change of paradigm.
We know that most companies use inventories to supply constantly goods to their customers. Now, let`s imagine that the company can instantly print the goods when required by customers. What would be the immediate consequence of this capability? No inventories required. That would subsequently reduce the costs for the company. On the other hand, the consumers who invest in 3D printing units (including hardware, software, and know-how) will be able just to print the desired product excluding the company mentioned above from the list of providers.
For the time being, the only problem that arises when analyzing the additive manufacturing versus traditional one is the cost per unit. Although 3D printing is more expensive than traditional manufacturing, its tooling cost is zero, meaning that for small productions runs, traditional manufacturing will remain more expensive than additive manufacturing. Even for large production runs, the 3D printing still has a competitive advantage if we take into consideration the printing time that could be shorter than the overall time for tooling the company.



Source: Bill Conerly (2014). Forbes. The Economics of 3-D Printing: Opportunities

Figure 2. Conventional manufacturing vs. 3D printing cost/unit

Nevertheless, this revolution will change our world. For the companies operating in the additive manufacturing industry and for the ones supplying the printing materials will represent a gold mine. Others will lose, being unable to adapt to the new trends and getting stuck to the old production ways.
Campbell *et al.* (2011) underlined that additive manufacturing industry raises some security issues, the technology enabling the production of goods that can harm people (weapons, ammunition, etc.)
According to Columbus (2015), "67% of manufacturers are already using 3D printing. Of these, 28.9% are experimenting to determine how 3D printing can be optimally integrated into their production processes. 24.6% are using 3D printing for prototyping."
In addition to the developments presented in Figure 1, Forbes (2015), citing a CSC study from 2012 emphasizes that the main industrial sectors that could benefit now and in the immediate future, from this new technology are:
- Defence and aerospace: weight reduction on aircraft, low volume parts;
The aerospace industry`s adoption of additive manufacturing is projected to increase to $3.45 billion by 2023 and in the automotive industry to $1.8 billion.
Boeing already prints parts for ten different aircraft; Lockheed Martin, Cincinnati Tool Steel, and Oak Ridge National Laboratory aim at printing endo- and exoskeletons of jet fighters for including the body, wings, internal structural panels, embedded wiring, and antennas; General Electric produces jet engines, medical devices, and home appliance parts; Aurora Flight Sciences manufactures unmanned aerial vehicles (D`Aveni, 2015).
- Automotive: design and prototyping and after-market customization, vehicle restoration

- Consumer and retail: novelty items, customized products, new in-store experiences and innovative marketing.

4. Economic implications of this new disruptive technology

The additive manufacturing could play a major role in the global economy enabling production to be relocated closer to the end consumer by addressing a market "characterized by customization, flexibility, design complexity and high transportation costs for the delivery of end products" (Berman, 2012; Gibson et al., 2010; Lipson & Kurman, 2013). D`Aveni (2015) gave us a hint of what 3D printing could mean for the economy "The U.S. hearing industry converted to 100% additive manufacturing in less than 500 days, and not one company that stuck to traditional manufacturing methods survived."

Based on its "unlimited" capabilities, 3D printing could lead to the development of an infinite variety of products since any technology holder can produce customized products.

The countries dealing with current-account imbalances could decrease their deficits by developing 3D printing industries that manufacture most of the goods they import. New industries and professions will be created to support this disruptive technology. The additive manufacturing commercial chain brings together related industries (3D printer producers, printing materials suppliers, parts suppliers, services providers (designers, intellectual property regulators, product engineering et cetera) enabling the emergence of new economic activities such as production and distributors of 3D printing cartridges, 3D printing software, production of scanners, etc. A relevant development model for the additive manufacturing could be the one followed by Hewlett-Packard, company that marked major profits by selling top quality printers and cartridges, creating a large commercial chain of trillions of dollars.

The development of large-scale 3D printing will gradually diminish the dominance of classical manufacturing industry, leading to job losses and structural change in the labour force in the global economy.

The 3D printing industries also have geopolitical implications. The countries that base their economic growth model on exports could record current account imbalances once their commercial partners start printing the goods they are currently importing. The key to prosperity will no longer be based on large manufacturing companies that have thousands of employees, but on companies that will provide high-tech printers and superior product designs. The large companies that outsourced their production abroad due to more competitive costs could reverse the process, repatriating their operations or changing the business model to 3D printing to be closer to the end consumers. The countries with trade deficits will become less dependent on their imports. When dependency decreases, negotiation power increases, resulting in new forms of agreement between countries. When important countries renegotiate their agreements, the geopolitical map tends to be redrawn.

5. Conclusions

As our paper emphasized, that 3D printing seems to play an important role in reshaping the economy of the future. The main identified advantages of additive printing are a cost reduction for customized small batches, shape flexibility of printed objects, eliminating tooling costs, saving raw material, greener technology, reduction in the design-to-manufacturing cycle, control of the entire value chain et cetera. Among the disadvantages, we can mention the cost of the printers, the printing speed, and the cost of printing materials. Just a handful of countries register over 75% of the 3D printing patents (China, Japan, USA, Germany, South Korea, and Great Britain). The top 5 companies producing 3D printers are located in just five countries (USA, China, Germany, Netherlands, and Sweden). The forecasted potential of the additive manufacturing industry varies from $4 billion to $13.4 billion in the next five to ten years.

Now, we can only estimate how this world will look like in the following years, with the help of the projections made by the specialist in the field. As additive manufacturing is gaining momentum, as happened before in the case of classical printing, the cost of production will decrease, and the manufacturing speed will increase, the technology having, thus, the power to level up the gap between the small and medium-sized companies, even start-ups, and the large enterprises. Siemens predicts that additive manufacturing will become 50% cheaper and up to 400% faster in the next five years (Columbus, 2015).

Sooner or later the companies will have to consider adopting this technology because the current business environment can be described in just two words: fast and changing. That means that the fast technological changes that characterize the IT&C industry, in particular, force the business environment to respond accordingly (Tunas, 2015). As D`Aveni (2015) emphasized, the U.S. hearing aid industry converted to 3D printing in just 500 days, the companies that delayed adopting the new production model didn't` survive on the market.

As the experts of Hudson Valley Economic Development Corporation underlined if only 10% of the global manufacturers begin employing 3D technology we will eventually see a $1 trillion industry.

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