

Adding it up: The economic impact of additive manufacturing

Written by:



About this report

Adding it up: The economic impact of additive manufacturing is an Economist Intelligence Unit report, sponsored by The Munich Technology Conference. In this paper, The Economist Intelligence Unit examines the economic implications of additive manufacturing processes and technologies.

The report builds on interviews with experts from academia and industry, together with secondary research, to explore the benefits and limitations of additive manufacturing, and the potential economic impact—on the distribution of global manufacturing, supply chains and business models—that could stem from its widespread adoption, in the short and long term.

2

We would like to thank the following interviewees (listed alphabetically by surname) for their time and insights:

- Martin Baumers, assistant professor of additive manufacturing management, Additive Manufacturing and 3D-Printing Research Group, Faculty of Engineering, the University of Nottingham
- Stefanie Brickwede, head of additive manufacturing, Deutsche Bahn, and managing director, Mobility Goes Additive
- Markus Kuhn, project manager and research engineer, German Aerospace Centre (DLR)
- Jérôme Rascol, vice-president of additive manufacturing, Airbus
- Douglas Thomas, research economist, Applied Economics Office, Engineering Laboratory, National Institute of Standards and Technology

Preface

The next steps are crucial

Much is being said and written about the enormous potential of additive manufacturing (AM). Day after day, new and fascinating examples are cited that highlight the upheavals this technology is bringing to industry. Anyone who has held a printed metal part of a complex organic structure in their hands and felt both the strength and lightness of the object understands what I mean.

A lot has already been achieved on the way to the widespread application of AM technology. But much remains to be done for its further industrialisation. On the one hand, AM is still not yet economical enough in many cases; on the other hand, qualitative maturity and reproducibility need to be improved. Although the technology is successfully used in the production of prototypes and individual parts that would be too expensive if traditionally made, AM offers far more—namely the potential to redesign the entire value chain.

The next steps being taken in the industrialisation process will be crucial: AM must prove that it not only has potential for designing, but that it—when used properly—also offers clear economic benefits. Achieving greater speed and efficiency in processes and improving the base materials are key. All players in the AM industry are challenged to pool their know-how and work toward these goals, in close partnership.

With its many years of experience in advanced materials, Oerlikon sees

itself as a co-ordinator and driver of the industrialisation of this revolutionary technology. In addition to conducting our own research on AM processes and materials, we are also focusing on networking potential partners from various industries as well as from the sciences and politics. In order to foster such exchanges, we founded the Munich Technology Conference (MTC), an annual two-day meeting that is being co-hosted this year by Oerlikon, Technical University of Munich, Bayern Innovativ and the industry partners GE, Linde, TÜV SÜD and Siemens. At the conference, we will discuss key issues related to the industrialisation of AM. Precisely these issues and their many aspects are explored here in this study.

Along with providing an in-depth look at the current state of AM, this study answers the question of just how far the technology has become established in different industries. At the same time, it examines where the AM industry needs to bundle its expertise so it can take the next decisive steps in the technology's development and implementation.

I wish you an interesting and informative read.



Professor Dr Michael Süss

Chairman of the board of directors, Oerlikon Group

Introduction

The invention and introduction of new manufacturing tools, techniques and processes can have profound impacts on the global economy. This has been demonstrated time and again in modern industrial history, from the introduction of the power loom and cotton gin during the first industrial revolution, through Henry Ford's moving Model T assembly line, to mass production injectionmoulding techniques or the just-in-time manufacturing processes pioneered by Toyota in the 1970s.

Each of these chapters of manufacturing innovation upended the established economics of production, to a greater or lesser extent, leading to significant impacts on the prices of goods, the dynamics of supply chains, business models and labour market conditions. The time and cost-savings that resulted from Ford's production line, for instance, enabled the company to slash the price of its cars, and pay wages that were unheard of elsewhere in the industry.¹ This, in turn, enabled newly enriched factory workers to participate in the growing economy as consumers in their own right.

Today, additive manufacturing (AM) technologies have the potential to create another wave of disruptive economic change. Broadly known as 3D printing, the technologies and techniques under this umbrella have been in development since the late 1980s, and have already found a number of uses in mainstream manufacturing, particularly in the medical, automotive and aerospace industries. Instead of creating objects by cutting away at raw materials, or injecting plastic or metal into pre-made moulds, AM methods deposit material layer by layer (see box on page 7). The technology has proved popular in the first instance for prototyping, but bears some promise to make industrial manufacturing more efficient by using fewer resources while making it easier and cheaper to build complex and custom one-off designs. Backers of the machines and techno-optimists herald nothing less than a revolution in manufacturing.

Adoption of AM is still, however, at an early stage. Sales of 3D-printed components have grown at a rate in excess of 25% per year since 1989, but still make up a small proportion of global manufacturing output. According to analysis from Wohlers Associates, a consulting firm and industry observer, AM accounted for less than a tenth of 1% of total manufacturing output in 2017.²

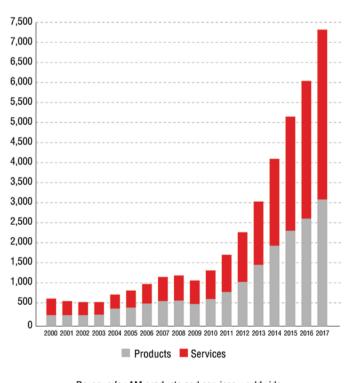


Figure 01 | Making it

Revenue for AM products and services worldwide. The market has grown by 5.5 times over the past eight years. (US\$ m)

Source: Wohlers Report 2018

The manufacturing industry as a whole makes up around 16% of the US\$80trn global economy, and, as such, even if AM captures only a small portion of this market, its adoption could still be significant. Furthermore, its impacts are expected by many to be greater than simple efficiency gains and reduced manufacturing costs that benefit manufacturers directly. It could extend to altering supply chains, trade norms and business models—with ramifications for the economy at large.

These wider implications are the focus of this report, which builds on interviews with experts and secondary research to explore the benefits and limitations of AM, and in particular the potential economic impacts of its widespread adoption. It finds that although the technology will probably only account for a small portion of the global manufacturing industry in the medium term, it could still have significant consequences in doing so.

The take-up of the technologies on a large scale could lead to a dramatic redistribution of where things are made, disrupting labour markets and having implications for the length and dynamics of supply chains in industries such as aerospace, medical and automotive, as well as companies in supporting industries such as transport and logistics.

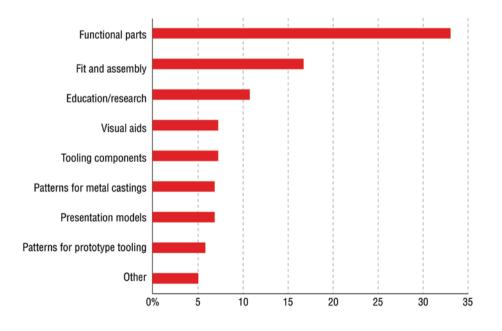


Figure 02 | AM in practice

How organisations are using industrial additive manufacturing systems, according to a survey of manufacturers, service providers and 3D-printer makers.

Source: Wohlers Report 2018

¹ The Henry Ford, Ford's Five-Dollar Day, https://www.thehenryford.org/explore/blog/fords-five-dollar-day/

² Wohlers Report 2018: 3D Printing and Additive Manufacturing State of the Industry, Wohlers Associates, http://wohlersassociates.com/2018report.htm

In particular, widespread adoption of the technology could move some manufacturing capacity closer to the end-user or customer, with some negative implications for low-skilled manufacturing jobs in low-wage economies. It is likely to simplify supply chains in industries such as automotive and aerospace, in particular, as goods can be made to order on-site rather than stockpiled and shipped, which could lower demand for existing transport and logistics services built around such supply chains.

AM could also disrupt engineering and design, as products and parts designed with AM in mind can be much more flexible in geometry and complexity, while using fewer resources. Moreover, AM processes are, in the long run, anticipated to make it easier for small companies to enter the market and for firms of any size to bring new products to market.

Although the majority of products will probably continue to be produced using conventional methods, even low levels of AM adoption are likely to have significant economic impacts in ways that are still becoming clear. As this report finds, much will depend on how businesses and innovators respond to the opportunities afforded by the technology.

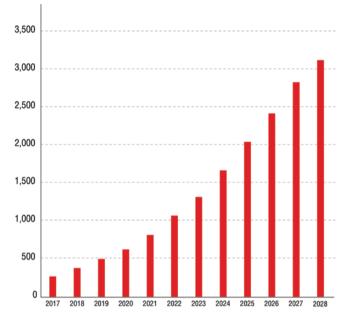
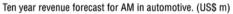
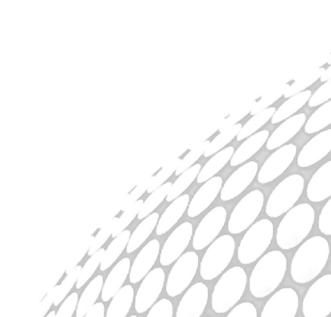


Figure 03 | Driving ambition



Source: SmarTech





How does additive manufacturing work?

In traditional manufacturing, products are generally created from raw materials using a conventional subtractive process such as machining or injection moulding. In additive manufacturing (AM), goods or parts are constructed layer by layer, according to the instructions of a digital file. There are seven defined methods of AM, depending on the desired cost, size and material of the finished product.³

Material jetting

This process uses a similar method to a 2D inkjet printer. A nozzle moves horizontally over the build surface, depositing material in drops, which solidifies and is then cured using ultraviolet (UV) light.

Material extrusion

In this popular method, common on many hobby 3D printers, material is drawn through a nozzle, heated and deposited layer by layer in a continuous stream.

Directed energy deposition

This is similar to material extrusion, except that the nozzle is not fixed to a specific axis and can move in multiple directions and at different angles. It's commonly used with metals, fed by either powder or wire.

Binder jetting

A liquid adhesive called the binder is deposited onto a bed of powdered material. Then another layer of powder is rolled across the build surface, sticking only to where the binder was placed. Alternating layers of powder and binder form the object.

Powder bed fusion

Commonly used for metals, this family of AM techniques uses a laser or an electron beam to melt and fuse powdered material in layers.

Sheet lamination

Thin sheets of material are bound together using either adhesive or ultrasonic welding for metals. A knife or laser cuts each layer to the required shape before the next is added.

Vat photopolymerisation

UV light is directed into a vat of liquid photopolymer resin, curing and hardening it where it hits. As each layer is completed a moving platform lowers the vat so the next layer can be cured.

Loughborough University, The 7 Categories of Additive Manufacturing, http://www. lboro.ac.uk/research/amrg/about/ the7categoriesofadditivemanufacturing/

01 / Material benefits

Additive manufacturing could cut the cost of complexity and customisation, and make manufacturing more efficient

The SMILE project is a European initiative to develop low-cost reusable rockets that launch small satellites into Earth's orbit. To ignite these rockets, a mixture of oxygen and kerosene is sprayed through a small injector and ignited. This injector is a complicated part that must withstand extreme heat and cold, and buffeting by mechanical forces.

To make it, Markus Kuhn of the German Aerospace Centre and his SMILE colleagues turned to AM, and a laser-beam melting machine from 3D Systems. "These injector elements contain hundreds of smaller parts assembled together," he says. Creating them using traditional methods would be very expensive and time consuming, and would involve detailed quality control checks to make sure each join and weld had been done properly. "It is much easier to achieve this with printing," says Mr Kuhn.

One of the foremost benefits of AM is that it can cut the cost of making these complex components. "In conventional manufacturing, there's quite a clear connection between the degree of complexity and the manufacturing cost," says Martin Baumers, an assistant professor of AM management at the University of Nottingham. With AM, on the other hand, "you can make really complicated shapes and they don't really cost anything extra." Mr Kuhn estimates that AM was three or four times faster and three times cheaper than producing the same injector using conventional means would have been. Instead of 35 different components being used for each injector nozzle, the part was produced in one go, skipping several production steps.

The technology can also allow for the creation of objects that would be impossible using other methods. The SMILE injector has tiny pressure sensor channels that could not have been made in other ways. "This kind of injector is only possible with 3D printing," says Mr Kuhn, adding that AM makes it much easier to scale the design up and down for different sized rockets.

Generally, designers and engineers have to think hard about how their designs will be manufactured and assembled, which limits what they can do, but designing for AM is different: it opens up new design possibilities. "We can make more functional components, things that deliver a higher stream of utility," says Mr Baumers.

However, there are some physical limits to what can be produced using the AM technologies of today. There is ongoing research work, but at present commercial machines can generally only print with one material, and can't yet integrate electronics or wiring into the objects that are created. "It's still a developing technology," says Douglas Thomas, a research economist in the Engineering Laboratory at the National Institute of Standards and Technology. "There are still things that are not completely known, like how some of these materials will perform under stress and strain."

Making manufacturing more efficient

Another benefit: AM can help create strong, light structures that wouldn't be possible using other methods.

In 2013 General Electric launched an international competition to redesign a bracket for a jet engine using AM. The winning entry, submitted by an engineer from Indonesia, was almost 84% lighter than the original component, but able to stand up to the same stresses and strains.⁴ Such lightweighting could have a significant impact on the overall performance and environmental cost of certain products. For example, as we move towards battery-powered vehicles, there has been an intense focus by car-makers on lightweighting, as every extra kilogram reduces the range.

AM can help improve the efficiency of existing products in other ways. For example, the blades of jet engines have cooling channels that allow them to operate at extremely high temperatures, at which blades without channels would melt. With AM, engine companies can create

Instead of 35 different components for each injector nozzle, the part was produced in one go, skipping several production steps.

Views from MTC² partner Siemens

AM as a game changer for the industry

AM augments traditional technologies to reimagine products, reinvent manufacturing and rethink business models.

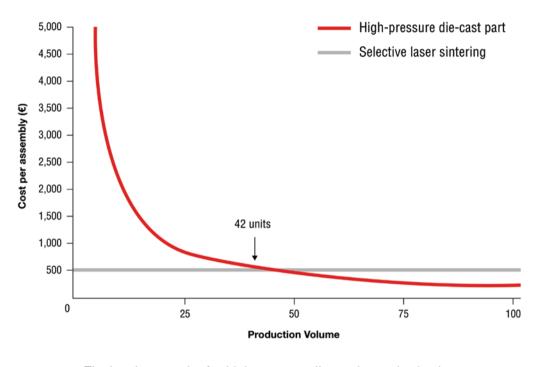
Prototyping and first use cases tend to capture the spotlight in AM. Maturing an industry from a well-established prototype to a series production status is the joint task of the whole AM industry, independent of the role along the value chain. We believe that industrial AM will be utilised by the automotive, aerospace, medical, machinery and energy industries in the future.

blades with much more complex cooling channels, making engines that can run at even higher temperatures, and are therefore cleaner and cheaper to run.⁵

It also allows for a more efficient use of materials. In traditional manufacturing, raw material is purchased from a supplier in the form of rods, plates or blocks and then cut down or worked on in a number of stages of machining to create finished products. This process inevitably ends up wasting a lot of the raw material. In AM, near net shape objectswhere the initial production is close to the final (net) shape-can be built up layer by layer, so much less is wasted. "In conventional manufacturing, there's an incentive to keep your component as close as possible to the raw material in terms of shape," says Mr Baumers. "That then produces parts that aren't really optimal during the use phase."

In the aerospace industry, for example, it has been estimated that by 2050 AM could save as much as 90% of raw material required in manufacturing.⁶ This could lead to significant

Figure 04 | Cost competitiveness of AM



The breakeven point for high-pressure die-casting and selective laser sintering, a powder bed fusion AM technique.

Source: Costs and Cost Effectiveness of Additive Manufacturing, National Institute of Standards and Technology (2014) ">http://dx.doi.org/10.6028/NIST.SP.1176/>

energy, and in turn cost, savings (see box on page 12). Over the long run these runningcost savings can substantially outweigh the larger upfront cost of manufacture.

It has been estimated that such savings could eventually make 3D printing cost competitive with traditional manufacturing methods for product runs of up to 14,000 units,⁸ or as high as 121,000⁹ units for small electrical components. However, that's some way off. "Right now, it's mostly costeffective for low-batch runs, where you're making 50 or 100 of something," says Mr Thomas. "Generally, it's not a cost-effective way of making a large number of products." Mr Baumers says the technology is proving its worth in niche applications, particularly for customised products, or in the rare instances where complexity needs to be mass-produced. "You need to find niches in which the average cost of conventional manufacturing processes is actually higher than the average cost of your additive process, and those do exist," he says.

One example is acetabular cups, a component of artificial hip joints. These parts are created en masse from titanium using an AM technique to create a complex, textured surface that improves osseointegration—how well the patient's bone melds with the implant. However, one added cost that is often overlooked is the increased cost of raw materials in the formats required for AM —which can more than cancel out any savings gained from using less material overall. "AM uses materials in non-standard shapes or forms," explains Mr Baumers. The hip implant requires titanium in powder form, which can cost almost ten times as much as other forms of the metal.

Polymers and plastics for industrial AM cost between US\$40 and US\$250 per kilogram, compared with US\$2-3 per kilogram for the materials used in injection moulding.¹⁰ "You use less material, but the material is really expensive," Mr Baumers says.

Figure 05 | Do material savings beat material costs?



Source: Ampower Insights; MetalMiner North American Titanium Index

It is expected that these costs will come down over time. "It's a chicken and egg issue," says Jérôme Rascol, head of AM at Airbus. "We have difficulties finding new business cases because of the cost, but on the other hand you need volume to decrease the cost."

Cutting the cost of customisation

In 2017 doctors at the Amiens-Picardie University in France were preparing to perform critical surgery on a six-year-old boy suffering from severe spinal issues. They combined scanning technology with 3D printing to create an accurate model of the boy's spine that enabled the surgeons to plan, practice and simulate the procedure in a risk-free environment, and to test a surgical robot that assisted in the operation.¹¹

This data-driven approach has already extended to other areas of the medical industry, where AM is being used to print custom implants, prosthetics, hearing aids and dental devices. It's also stretching to the consumer market—Adidas and New Balance are among the sportswear brands using AM to create custom footwear for elite athletes, tailored to their foot shape and running style.¹²

As well as cutting the cost of complexity, AM can also slash the price of variety, by making it easier and cheaper for factories to switch between making different types of product. On a production line, making something new means bringing in new materials, new machines and resetting equipment. In some industries, these changeovers can take weeks, and come with installation costs and the expense of storing machines that aren't in use.

For traditional means of production such as injection moulding, these "tooling costs" are significant, accounting for as much as 93.5% of traditional manufacturing costs,¹³ while in AM the only outlay involved is in updating the design files.

"You have much larger operational flexibility," says Mr Baumers. "We don't

have any tooling, or any fixed process for parts that are the same over large process runs, which means lead times are reduced, and you can change over much more easily if other products are required."

The cost of such items will remain prohibitively expensive in the short term, which may limit its desirability for mass-market applications elite athletes may be the only ones who find it affordable to 3D print their shoes. But for high-value products it is already proving a useful tool—the market for 3D-printed medical devices is expected to reach US\$2.3bn by 2020, for example.¹⁴

Instead of economies of scale, AM can, as such, create "economies of scope". As there are fewer costs associated with switching between making different things, adopting the technology makes it easier for companies to bring a range of products to market.

Views from MTC² partner GE Additive

AM's time is now

AM is disrupting conventional manufacturing supply chains, shifting how and where parts and systems are made. This disruption creates a ripple effect throughout the entire value chain that is impacting multiple industries, raw material needs, energy requirements, freight logistics, engineering services, construction and the balance of trade—worth around US\$33trn today globally, according our own internal research, based on global macro-economic indicators. AM is also driving a rethink of expectations for future jobs and skills, while advances in design engineering, software and materials science are positively contributing to the impact and potential the technology brings.

- ⁴ GE Reports, Jet Engine Bracket from Indonesia wins 3D Printing Challenge, https://www.ge.com/reports/post/77131235083/jetengine-bracket-from-indonesia-wins-3d-printing/
- ⁵ MITSIoan, Getting Past the Hype About 3-D Printing, http://www.parthv.com/wp-content/uploads/2017/07/Bonnin-Roca_Vaishnav_etal-2017-Getting-Past-the-Hype-About-3-D-Printing.pdf
- ⁶ https://www.sciencedirect.com/science/article/pii/S0301421517306997
- ⁷ L A Verhoef et al, The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach, 2018, Energy Policy, https://doi.org/10.1016/j.enpol.2017.10.034
- ⁸ N Hopkinson and P Dicknes, Analysis of rapid manufacturing—using layer manufacturing processes for production, Journal of Mechanical Engineering Science, 2003, http://dx.doi.org/10.1243/095440603762554596
- ⁹ E Atzeni et al, Redesign and cost estimation of rapid manufactured plastic parts, Rapid Prototyping Journal, 2010, http://dx.doi. org/10.1108/13552541011065704
- ¹⁰ Wohlers Report 2018
- ¹¹ 3D natives, Surgeons use 3D printing to fix 6-year-old boy's spine, https://www.3dnatives.com/en/surgeons-3d-printingspine-131020174/
- ¹² The Wall Street Journal, Is Mass Customization the Future of Footwear, https://www.wsj.com/articles/is-mass-customization-thefuture-of-footwear-1508850000
- ¹³ Nourredine Boubekri and Meshari Alqahtani, Economics of Additive Manufacturing, 2015, International Journal of Advances in Mechanical & Automobile Engineering, http://iieng.org/images/proceedings_pdf/7435E0915066.pdf
- ¹⁴ Allied Market Research, Press Release, https://www.alliedmarketresearch.com/press-release/3d-printing-healthcare-market.html

Additive manufacturing could cut global energy use by as much as

27% by 2050

Source: Delft University of Technology

01 / Material benefits

Could additive manufacturing cut energy use?

Additive manufacturing could cut global energy use by as much as 27% by 2050, according to an assessment of energy savings in two major industries conducted by researchers from Delft University of Technology.⁷

Aerospace

Potential energy savings in the aerospace sector range from 5% to 25%, owing in part to material savings (0.132 exajoules, or EJ) and parts no longer needing to be transported to and from low-wage economies to be worked on (1.22 EJ). The greatest savings would stem from lighter planes: estimated at 7.37 EJ per year for the world fleet.

Construction

Potential energy savings in the construction sector range from 4% to 21%, with a significant amount of energy (39.8-43.3 EJ per year) saved due to the drop in the amount of materials required, and the energy required to move those materials (3.2-3.44 EJ per year).

02 / Does additive manufacturing add up?

The limitations and challenges of additive manufacturing

The adoption of AM tools and techniques is not without its challenges. Ever since AM technology entered the mainstream consciousness with the release of the first "desktop", plastic-modelling 3D printers in the mid-2000s, the media has described the near-future possibility of a world of plenty, where everyday citizen makers could print everything we needed at home at the press of a button.

Despite the potential economic benefits of AM, there are a number of drawbacks that could limit its adoption, and therefore its impact on the global economy, suggests Mr Baumers. "People have been claiming that we'll start manufacturing at home for quite a long time, and I think that's completely wrong," he says. "It ignores the fact that most people don't want to design or manufacture anything."

Analysis from Wohlers Associates suggests that no more than 5% of manufacturing will be additive in future. Other estimates put the figure at 10% at most.¹⁵ "Not everything that can be 3D printed will be 3D printed," says Mr Baumers.

For basic objects with simple geometry, AM is often slow and expensive in comparison, which means it is unlikely to ever replace mass production for the majority of basic products. "Consider the cost of printing a simple object like a spoon on a 3D printer, for example, it's going to be less expensive to make that with traditional manufacturing methods," says Mr Thomas. Machine costs can be as high as 70% of the total cost of a 3D-printed item. And, as described in chapter one, although much less material is used to create each object, the cost of raw materials is much higher. Material accounts for 30% of the total cost of a 3D-printed item, on average, compared with less than 3% for traditional manufacturing techniques.¹⁶ These figures vary depending on the price of the machines and the materials, how fast the machines can print (the build rate, measured in cubic centimetres per hour, which reduces the machine cost) and

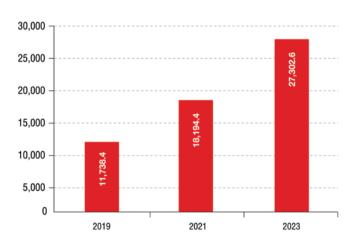


Figure 06 | Estimated future penetration of AM

Forecasts suggest that the sales of AM products and services will grow by 3.7 times from 2017-23, to a US\$27.3bn industry. (US\$m)

Source: Wohlers Report 2018

how much they are in use (the machine cost per item falls the more the machines are used).¹⁷

Items made with AM are rarely ready to go straight out of the printer, either—they may require post-processing in the form of sanding and smoothing, or assembly. This is usually done by hand and adds to the cost of the finished item. For the SMILE rocket injector, for instance, the printing process is only one part of a ten-step process. For a simple titanium-alloy aerospace component, such costs can make up 10-15% of the total cost of the component.¹⁸ Staff costs for machining and other manual post-processing account for 30% of the cost of AM production, according to Stefanie Brickwede, head of AM at Deutsche Bahn, a German railway company.

There are production uncertainties to reckon with, too. In manufacturing processes that begin with a block of material where you cut away what you don't need, you can be reasonably certain that the material you end up with will have the same internal properties as what you started with. That's not the case with AM. The same design printed on one printer, or in one building, could turn out completely different on another printer or somewhere else, depending on the environmental conditions, the material, or even the operator. Improvements in the technology can help better control variations in temperature and humidity, but many variables need to be controlled, and not all of them are specified in the design file. "The cake looks the same, but it's different, and it will not work as intended," says Mr Baumers.

This means that critical parts need to be thoroughly checked and verified to make sure they actually have the structural integrity implied by the design file. "The big issue is the certification process," says Ms Brickwede at Deutsche Bahn. "If we want to bring those parts onto the trains we have to prove that they are exactly as secure and safe as the technologies that we used before. We have to prove this with each and every part, which is an awfully expensive and long process."

Ultrasound can be used for checking the integrity and quality of some objects, but not for all metals. Industrial computerised tomography (CT) scanning is slow and expensive, and doesn't work for certain complex shapes that you might turn to AM for in the first place. This is less of a problem for low-batch industries such as aerospace, but is a big barrier to mass production.

As such, AM lacks efficiency at scale. Some companies have managed to get around these problems by very tightly controlling environmental variables and making the same things in the same way each time, but by doing so they lose much of the operational flexibility that makes AM an attractive proposition. "AM processes emerged from prototyping, so they weren't really designed for manufacturing and they're not particularly stable in the way they work," says Mr Baumers. "That means you're going to have guite a bit of build failure and product rejection."

Views from MTC² partner Bayern Innovativ GmbH

AM is a key technology of digitisation. AM comprises a wide range of different processes and materials as well as a great potential of applications in many different industry sectors. It is obvious that the economic impact of AM will be enormous. It will change classical value chains and create new business models. Thus, AM is a major technology for the future and for Bavaria as an industry location.

Additive manufacturing keeps Deutsche Bahn on track

Deutsche Bahn, a German railway company, started using additive manufacturing (AM) at the end of 2015. The company began by trying to identify the perfect use cases for the technology. Although the immediate uses for many businesses are in prototyping, Deutsche Bahn does not really produce its own products, and so decided to focus on the production of spare parts that could immediately be used in trains and railway infrastructure.

The first part the company produced was a plastic coat hanger for some of its older trains, which was no longer available on the open market. To date, Deutsche Bahn has printed more than 100 different designs, including large metal items. The key benefit, says Stefanie Brickwede, Deutsche Bahn's head of AM, is not only savings, but the ability to improve the capabilities of its trains and infrastructure through speed and customisation. Without AM, it can sometimes take up to two years for parts to be available from the market, she says.

The company is also using AM to print signs with Braille to help visually impaired people find their way around stations. "This is a brilliant use case of 3D printing," says Ms Brickwede, who is also the managing director of Mobility Goes Additive, an organisation aimed at increasing the use of AM in the transport industry. "We improved the comfort of our disabled passengers and we were able to cut the cost in half."

Deutsche Bahn believes that approximately 3% of its spare parts can be printed in this manner, but that this will increase over time. "At the moment the technology is still quite expensive, but costs are decreasing and the technology is improving," says Ms Brickwede. "We need more materials and very specific ones, a clear legal framework, and more people who are educated in AM." Despite the hidden costs and challenges, costs are generally falling as companies learn to use the process more efficiently, according to the interviewees we spoke with for this report. For example, one key determinant of overall cost, according to Mr Thomas, is how much of the build volume inside a printer is used up within each print run. Over time companies will learn to optimise their processes to make the most of their machines—how well they can manage these costs will ultimately determine the cost-effectiveness of AM in future.

The technology is also improving at a rapid rate. In 2016, for example, HP released its Multi Jet Fusion 3D printer, which it claims is 50% cheaper and ten times faster than other models for plastics. New research is focusing on reducing the amount of waste in techniques such as powder-bed fusion, which will bring material costs of that technique down further, too. "As AM becomes adopted more, economies of scale will drive the materials cost down, and it will probably do the same thing with AM systems," adds Mr Thomas.

These challenges have punctured some of the early hype around AM. It's telling, says Mr Baumers, that many of the companies that have been working with AM in the prototyping world are yet to adopt it at a larger scale. But there are still significant opportunities ahead.

- ¹⁵ Ruth Jiang et al., Predicting the future of additive manufacturing, Technological Forecasting and Social Change, https://doi. org/10.1016/j.techfore.2017.01.006
- ¹⁶ Nourredine Boubekri and Meshari Alqahtani, Economics of Additive Manufacturing, 2015, International Journal of Advances in Mechanical & Automobile Engineering, http://iieng.org/images/ proceedings_pdf/7435E0915066.pdf
- ¹⁷ NIST, Costs and Cost Effectiveness of Additive Manufacturing, https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST. SP.1176.pdf
- ¹⁸ MITSloan, Getting Past the Hype About 3-D Printing, http://www. parthv.com/wp-content/uploads/2017/07/Bonnin-Roca_Vaishnav_ et-al-2017-Getting-Past-the-Hype-About-3-D-Printing.pdf

Views from MTC² partner Linde

AM will be a catalyst for profound changes to traditional capital-intensive manufacturing business models. Accelerated product development, reduction or elimination in tooling costs and materials waste, design autonomy, reduced obsolescence and production nearer to the point of use will have a significant impact on the economy. AM will speed time to market, reduce product launch risk, enhance product value, enable the circular economy and influence companies' manufacturing footprint. High purity industrial gases and gas technologies will be fundamental to optimising processes across the AM value chain, from powder production and printing to post processes. It will also enable industry to create their own tooling and spare parts, improving efficiencies and lowering costs.

03 / Making a difference

The adoption of additive manufacturing could have widespread effects on global manufacturing productivity, supply chains and business models

Distributed manufacturing

In Volkswagen factories, workers are always on the lookout for custom tools that can help make their lives easier when assembling vehicles. Instead of outsourcing the design and manufacture of these products, the company has recently taken to printing many of them using desktop-class 3D printers, in the same factories where they're needed. New time-saving items can be suggested and designed by workers, and then printed overnight, incorporating rounds of employee feedback until the perfect tool is made. For example, a wheel protection jig, used to hold the wheel in place, was previously sourced by the company in 56 days for €800, but now can be printed in just 10 days for €21. In 2016 the company saved an estimated €150,000 by printing these parts in-house instead of going to external manufacturers.¹⁹

The ability to manufacture products in this way, whether on desktop-class or industrial machines, much closer to the end customer could have a significant economic impact right through the supply chain. Some analysts and observers envisage a network of "neighbourhood" print shops creating products for various industries.

"Orchestrating AM technology will be a huge business opportunity in the future," says Mr Baumers. Print brokers could sit between the companies running the machines, and the companies that need components helping to optimise the workflow. This would provide the printing companies access to a fixed order stream, and help companies that needed AM to access the technology.

However, there are still economies of scale associated with AM, and it may not be that straightforward to set up factories in every city. Skilled technicians are required to operate the machines and, as a result, even with the savings on transport and warehousing it may still be cheaper to have one person operating

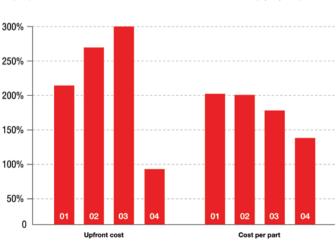


Figure 07 | Counting the costs of AM

This chart demonstrates the current and anticipated upfront cost and cost per part associated with conventional and additive manufacturing (AM) adoption.

01_Conventional manufacturing (offshore) 03_AM at current performance, 02_Conventional manufacturing (onshore) 04_AM at forecasted mature performance.

> Source: Figures and analysis from Environmental and Economic Implications of Distributed Additive Manufacturing, Journal of Industrial Ecology (2017)

ten machines in one location, instead of hiring ten people in different locations to facilitate more distributed manufacturing.

Chain reaction

AM could also cut costs in other areas, such as warehousing. John Deere, an American producer of agricultural equipment, has to provide a lot of spare parts—its depot in Milan, Illinois, ships out more than 450,000 orders a week.²⁰ Getting them to customers quickly requires a lot of storage space, and so the company has been working with Carbon—a supplier of AM equipment—to introduce "e-warehousing". Instead of storing components in a physical warehouse, the company will store designs for them in the cloud, which can then be transmitted to 3D printers in different locations and made to order.

By the time AM reaches full market potential around 2060 by some estimates²¹—such a shortening of supply chains could significantly disrupt the economy. AM could lead to a

We have €600m worth of parts in stock, just for rolling stock. If we can reduce this by printing on demand, this will be pure cash. This will affect contract logistics dramatically.

Stefanie Brickwede, Deutsche Bahn simplification of supply chains, says Mr Thomas. Instead of ordering parts and storing them in a warehouse until they're needed, or using complex just-in-time processes, manufacturers will be able to print parts on demand in the same location where they're needed.

At Deutsche Bahn, Ms Brickwede says her company is exploring this opportunity. "We have €600m worth of parts in stock, just for rolling stock," she says. "If we can reduce this by printing on demand, this will be pure cash, and this will be possible in the future. This will affect contract logistics dramatically."

"If AM develops to the level where it can produce complex assemblies like a transmission for a car, that could reduce a lot of the supply-chain touchpoints," says Mr Thomas. In theory, it could put the existing suppliers of parts for that transmission out of business.

Others aren't so sure. "It's easy to build a narrative that because we have AM, we don't have to hold stock anymore, but at the moment that's a step too far," says Mr Baumers, who points out that most early adopters of the technology have been highly vertically integrated companies that tend to already make their own parts in-house anyway.

At present, neither Airbus nor Deutsche Bahn are seeking to replace their supply chain with in-house AM. Instead, they're putting systems in place to help their suppliers use the new technology. "The idea is to allow the supply chain to be in a position to improve their offers using AM," says Mr Rascol.

Deutsche Bahn currently uses a network of external printing suppliers to meet their needs, and has created a network called Mobility Goes Additive to help support the industry. "We rely 100% on printing service providers," says Ms Brickwede. "These are experts on how to deal with machines. Our task is identifying the right use cases."

Nonetheless, AM has the potential to reduce the cost of supply-chain management, and decrease vulnerability to supply-chain disruption.

Labour market impacts

In tandem, distributed production and the simplification of supply chains could have a significant impact on the labour market. Because AM is well suited to making complex or custom products, it could replace manual processes such as welding and machining for items that can't be replicated en masse using current technologies, automating a substantial chunk of manufacturing. The impact of this is already being felt in the field of prototyping, where AM has largely displaced the small-scale models and iterations that used to be produced by hand.

Adopting AM also requires a highly skilled workforce, with a substantially different skillset from that cultivated from more conventional manufacturing techniques. Because of this, it has been argued that AM will help bring jobs back to advanced economies from lowwage economies in Asia and elsewhere.²² "AM is an advanced technology, so I would see advanced economies having a higher advantage in that space," says Mr Thomas. Dental company Albensi adopted AM in its production process and now employs 160 people in the US instead of outsourcing production to China, for example.²³

However, given the current high cost of AM, few see its adoption hollowing out manufacturing jobs in low-wage economies yet, particularly because much of the postprocessing work required for printed parts is still done by hand. A study in Sweden found that although AM contributed to job creation in product development and manufacturing, it did not bring back mass production jobs from emerging economies, because traditional manufacturing methods were still perceived to be more profitable.²⁴

Longer term, as costs go down, AM will likely be a democratising force for smaller business and international competition. As we have found, tooling and retooling can swallow up to 93.5% of traditional manufacturing costs²⁵ —without them, smaller companies will find it easier to bring products to market.

A company with an innovative idea will not have to spend money on machines, factory time or warehousing. Instead, they can carry out smaller production runs, or even print on demand in response to orders coming in. Manufacturers both large and small will be able to respond to customer demand more quickly, as AM can speed up both design iteration and production. This would reduce risk, as it will be more straightforward to make minor product adjustments without making major changes to the manufacturing process.

AM also changes the relationship between capital and scope, reducing the cost of expanding product lines or trying new products. This could affect how new products are designed, and how quickly they come to market. Instead of spending months and years on careful market research, product designers can try lots of different items and see what works. This could make the easy innovation we've seen in the software industry a reality for physical products too.

"The democratisation of the technology could lead to some kind of culture change," says Mr Rascol, who believes that the first generation

03 / Making a difference

of designers raised with AM will make full use of the increased design freedom that it offers.

However, some express concerns that, as physical production evolves to have more in common with the economics of digital production, it could also make counterfeiting and imitation easier-the value of a product will no longer be in the physical item, but in its design. In theory, instead of buying a replacement for a particular component, companies could scan it and print out a replica. There could be echoes of the digital revolutions in the entertainment industry, where piracy blossomed and digital copies of music and movies were shared freely, with no benefit to the original producers. In 2014 Gartner predicted that intellectual property losses due to AM would reach US\$100bn by 2018.

That scenario hasn't come to pass, partly because, as Mr Baumers points out, there's more to it than just 3D-scanning an object and printing out copies. "There's a lot of know-how and tacit knowledge in implementing 3D printing," he says. "While you might not have tooling expense, setting up a really flexible AM process that can handle all sorts of variation is difficult."

However, there could still be a significant economic impact. AM will remove some of the first-mover advantage that companies have from being the first to figure out how to manufacture a product.

There is also a growing open-source community, sharing designs for free particularly in the robotics and prosthetics industries. One study of the US toy market estimated that consumers could save as much as US\$60m a year by printing off toys instead of buying them.²⁶

Views from MTC² partner TÜV SÜD

The future economic relevance of AM depends on entrepreneurs' ability to establish new business models while developing manufacturing solutions.

After more than 30 years of developing solutions within the AM segment, the current third implementation wave will bring the next generation of systems, delivering significantly lower manufacturing costs and increased business model transformation capability. This improvement will gradually exploit technological potential and redesign value propositions. Therefore, it is already economically relevant. Companies that do not invest in gaining key expertise minimise their future market share in this high potential segment.

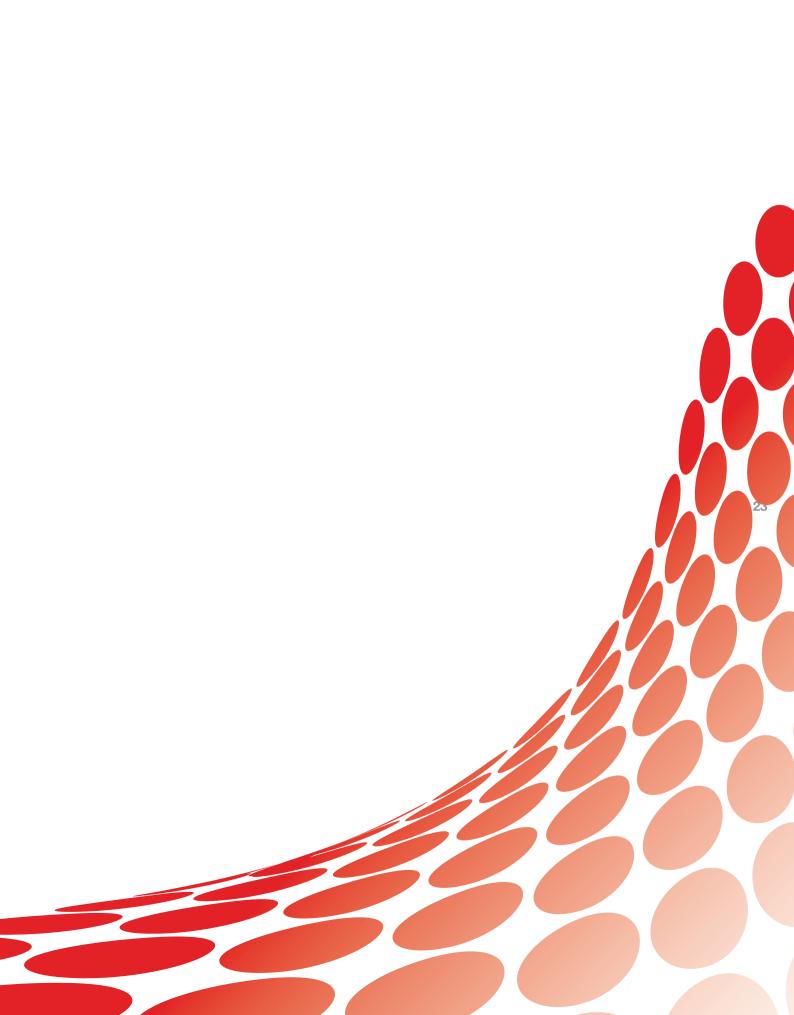
- ¹⁹ TCT Magazine, Can you jig it? 3D printing inside Volkswagen Autoeuropa, https://www.tctmagazine.com/can-you-jig-itvolkswagen-ultimaker-3d-printing/
- ²⁰ John Deere, Parts Distribution Centers, https://www.deere. com/en_US/parts/distribution_network/distribution_centers/ distribution_centers.page
- ²¹ NIST, Costs, Benefits, and Adoption of Additive Manufacturing: A Supply Chain Perspective, https://www.nist.gov/publications/ costs-benefits-and-adoption-additive-manufacturing-supplychain-perspective
- ²² Sheffield Hallam University, Investigation on Additive Manufacturing as an enabler for reshoring manufacturing activities, http://shura. shu.ac.uk/16265/1/Hamid%20Moradlou%20EUROMA%20 Conference%20Paper%20%281%29%20%281%29.pdf
- ²³ Advanced Manufacturing, Teeth Being Restored and Jobs Being Reshored, https://advancedmanufacturing.org/teeth-restoredjobs-reshored/
- ²⁴ B Kianian et al, Exploratory Case Study of Suppliers of Additive Manufacturing in Sweden, 2015, Procedia CIRP, https://ac.els-cdn. com/S2212827114009226/1-s2.0-S2212827114009226-main.pdf
- ²⁵ Nourredine Boubekri and Meshari Alqahtani, Economics of Additive Manufacturing, 2015, International Journal of Advances in Mechanical & Automobile Engineering, http://iieng.org/images/ proceedings_pdf/7435E0915066.pdf
- ²⁶ CBInsights, From Construction To Art, Here Are 25 Industries That 3D Printing Could Disrupt, https://www.cbinsights.com/research/ report/3d-printing-technology-disrupting-industries/

Conclusion

Unlike other significant innovations in manufacturing history, AM is unlikely to topple and replace existing production methods. Its adoption may only forge a small part of the global manufacturing industry. There remain issues with the cost of the process and the materials required that make AM simply uncompetitive with conventional manufacturing methods when it comes to much mass manufacturing. But as this report has found, the promise of AM is that it affords entirely new capabilities for manufacturers and, in turn, everyday businesses.

Adopting AM can cut the cost of developing complex products, increase creative freedom, and make manufacturing more efficient. In the short and medium term, AM technologies remain best suited to small-batch, custom and niche applications in aerospace, medical and automotive industries. Given the size of the global manufacturing market, even low levels of manufacturing adoption are likely to have a significant economic impact in ways that are still becoming clear.

As adoption increases and the technology improves, AM could lead to a broader redistribution of manufacturing, moving many instances of production closer to the end consumer, with resulting changes to the labour market both in advanced and in low-skilled labour markets. These shifts will also result in a simplification of supply chains, as parts and products are printed in-house instead of being assembled using components from multiple suppliers, leading to knock-on effects in the transport and logistics industries. In combination with artificial intelligence, and other advanced technologies, AM could further change the way products are designed, and make it much easier for smaller companies to enter the market on an even footing with existing, capital-intensive incumbents. Overestimated in the short term, the long-term impacts of AM could be profound.



About the sponsor



2 2nd Munich Technology Conference October 10-11th 2018 Technical University of Munich, Germany

The Munich Technology Conference is a conference series dedicated to discussing up-to-date technology topics. The event brings together leading stakeholders of additive manufacturing (AM) to discuss trends, innovations, processes and where the industry is heading. It offers a platform for leading experts from the corporate, academic and political sectors to discuss the latest developments in AM. Participants get the opportunity to interact with and learn from pioneering practitioners.

The 2nd Munich Technology Conference co-hosted by Oerlikon, Technical University of Munich, Bayern Innovativ and the industry partners GE, Linde, TÜV SÜD and Siemens will advance discussions among worldrenowned decision-makers and leaders from industry, academia and politics.

```
www.munichtechconference.com
#mtc2
#industrializeAM
```

