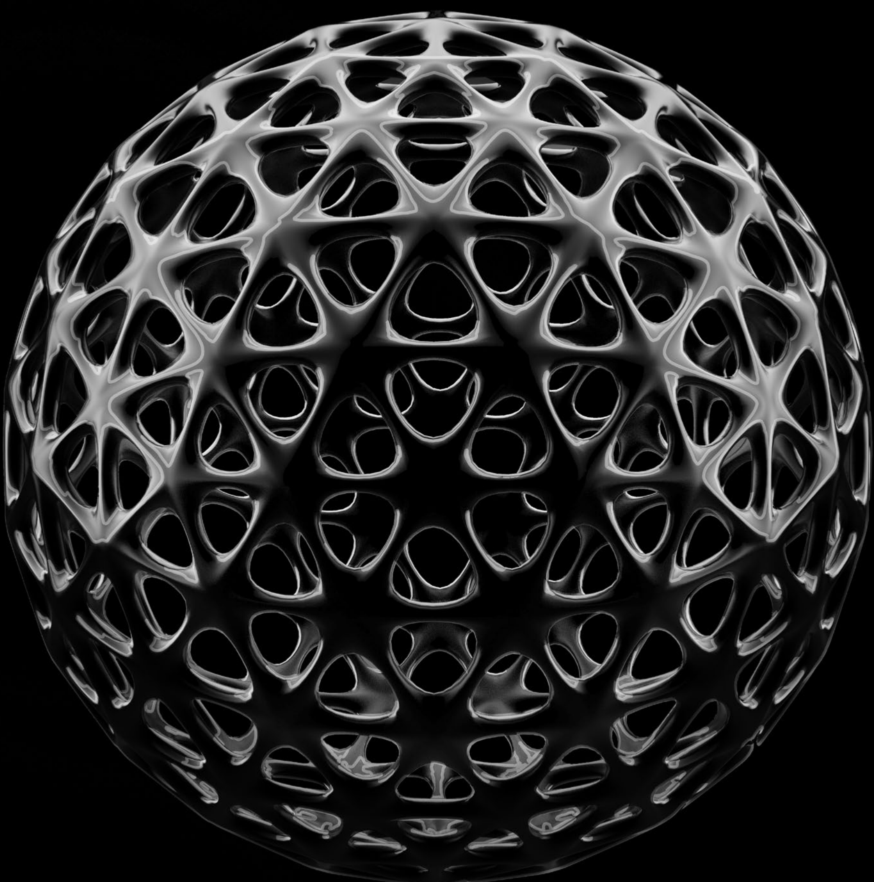


Challenges of Additive Manufacturing

Why companies don't use Additive Manufacturing in serial production

Technology and History

Despite its potential, many organizations have not expanded the role of Additive Manufacturing (AM) since its inception in the mid-1980s. AM, often called 3D printing, refers to a group of technologies that create products by adding material rather than subtracting it.

Based on a digital model, the objects are made by depositing a constituent material, or materials, onto a substrate layer by miniscule layer. The tools used to layer the material in this procedure are digitally controlled and operated.

These technologies can be clustered into different computer-controlled processes, distinguished from one another chiefly through the way the layer structure is built and the liquid or solid material used.

The different AM production processes include sheet lamination, extrusion deposition, granular material binding and light polymerization, which are used in various applications for multiple industries, including automotive, aerospace, machinery, healthcare and consumer goods. The most important technologies in use today are Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Melting (SLM), Stereolithography (SLA) and PolyJet[1], with metals, plastics, ceramics and composites as the main materials (see Figure 1).

Additive Manufacturing is a production process in which a three-dimensional object is created by building up one layer of material at a time using digital 3D model data.

[1] Statista – https://de.statista.com/statistik/daten/studie/760408/umfrage/meistgenutzte-3d-druck-technologie/

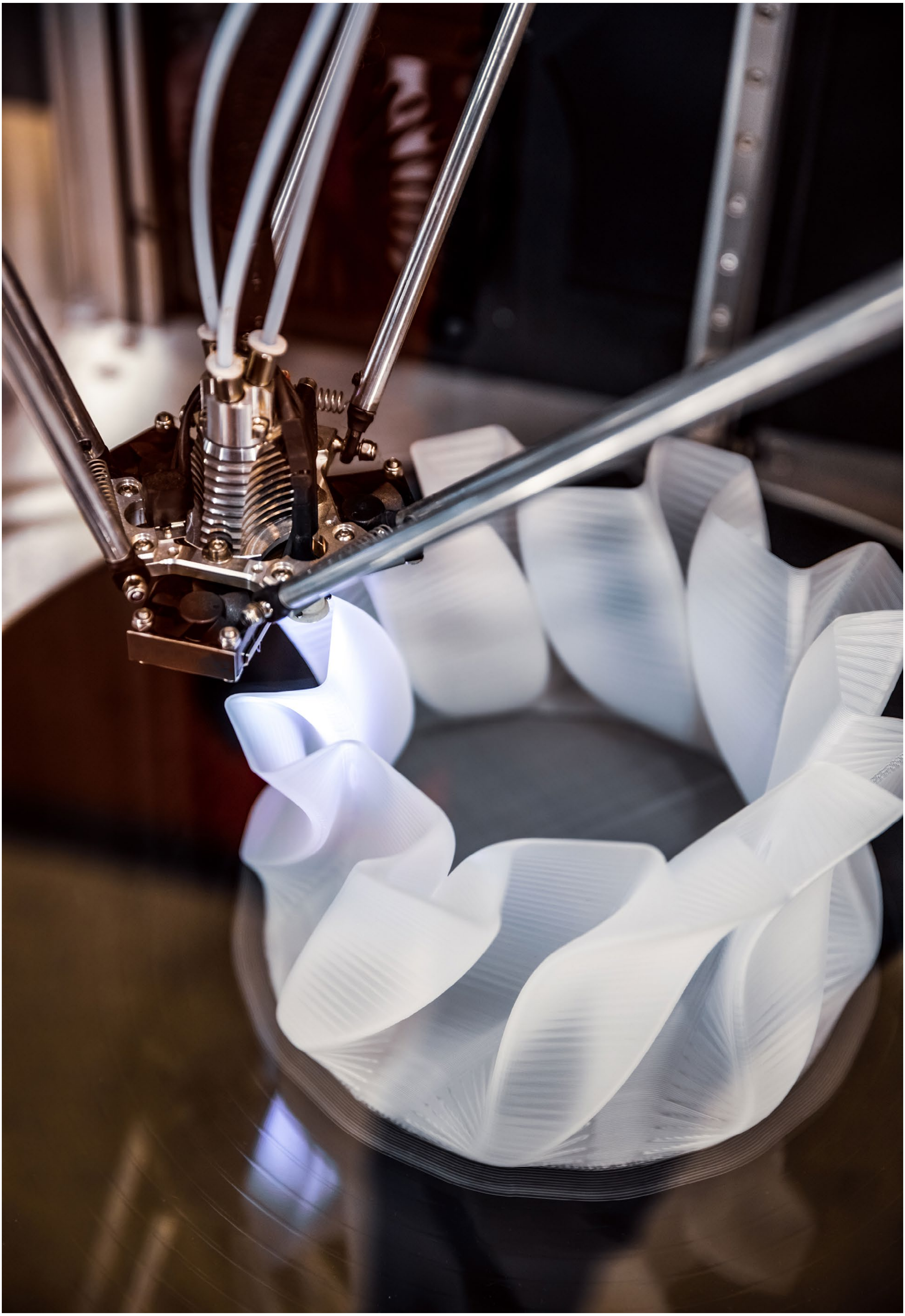
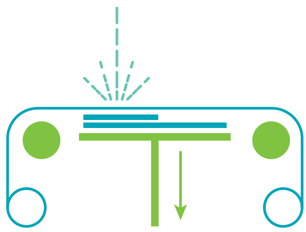
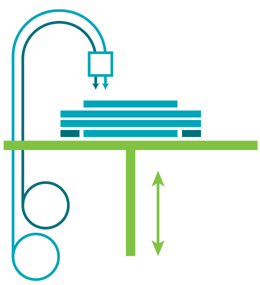
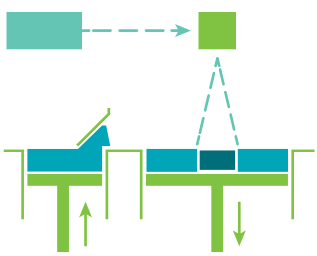
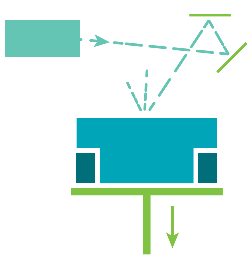
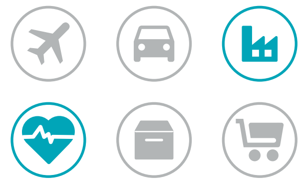


Fig. 1 – Additive Manufacturing processes and technologies with typical material, application and industry

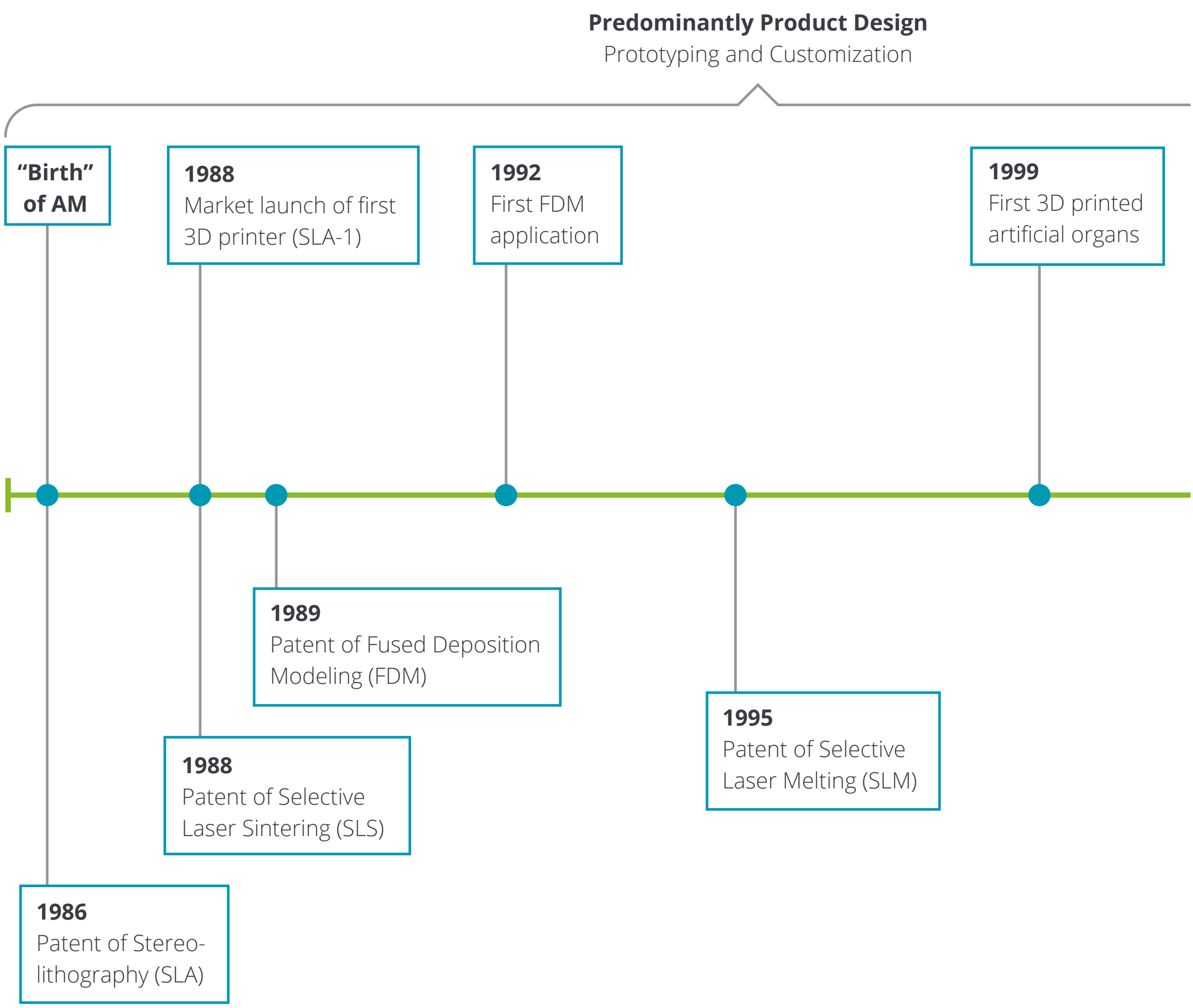
Process		Technology
Sheet Lamination 	Thin layered sheets of metal or plastics are bound together using welding or adhesive. The desired form is cut by a laser or blade	• Laminated Object Manufacturing (LOM) • Ultrasonic Additive Manufacturing (UAM)
Extrusion Deposition 	Build material on a coil is melted in a heated extrusion nozzle moving across the X-Y plane and selectively depositing material	• Fused Deposition Modeling (FDM) • Plastic Jet Printing (PJP)
Granular Materials Binding 	Material in a granular bed is sintered into a solid layer by layer using a laser or print head. The unfused material is used to support overhangs and thin walls	• Selective Laser Melting (SLM) • Direct Metal Laser Sintering (DMLS) • Electronic Beam Melting (EBM) • Selective Laser Sintering (SLS) • Binder Jetting
Light Polymerization 	Ultraviolet light converts drops of a liquid plastic or resin into a solid through a curing process	• Digital Light Processing • Stereolithography (SLA) • PolyJet • Film Transfer Imaging

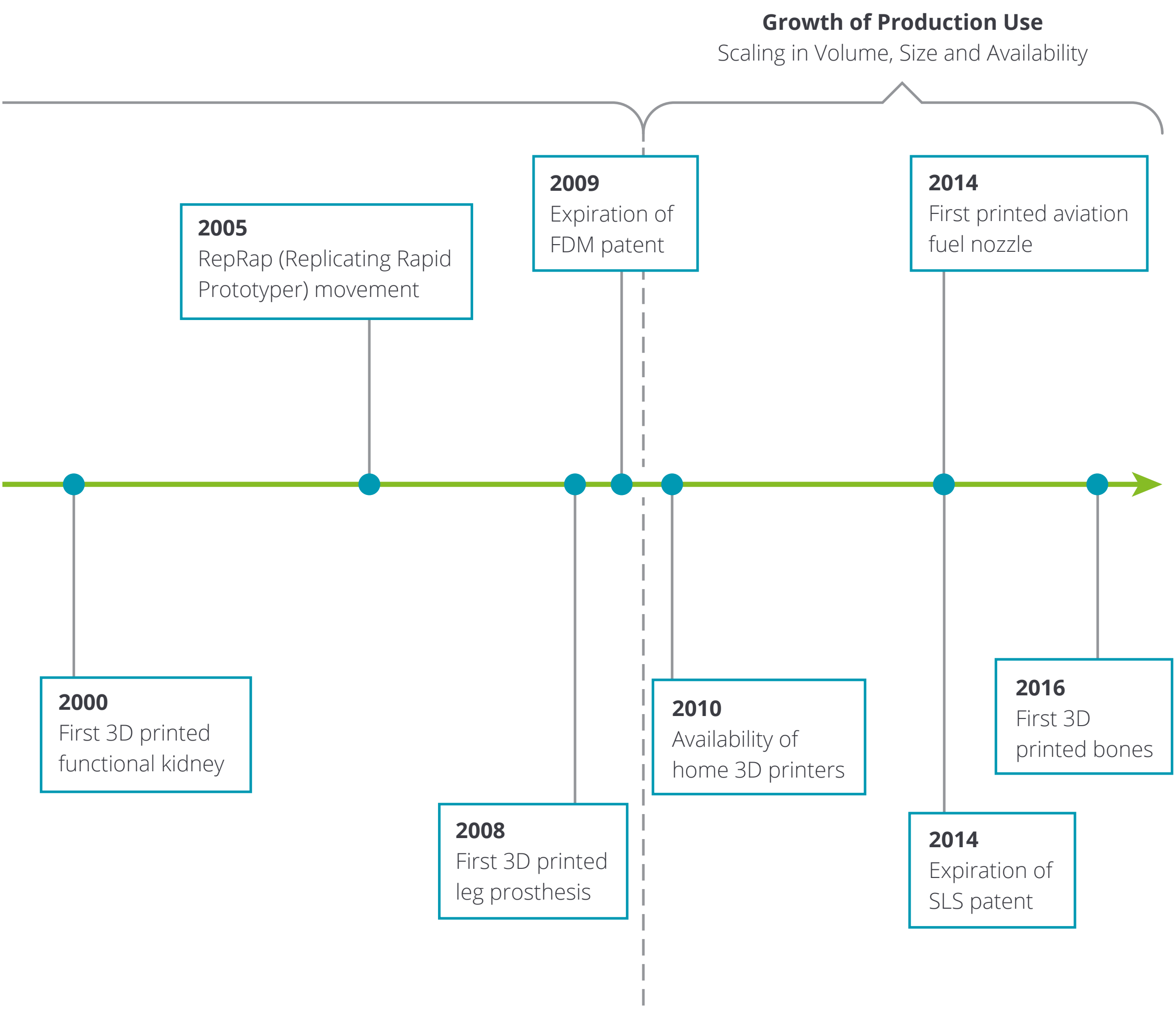
Material	Usage	Industry
	• Easy handling and fast, low cost manufacture of large parts • Limited strength and durability depending on welding and adhesive • Not suitable for making structural or functional models	
	• One of the most commonly used AM processes • Builds strong, complex parts, but slower method • Suitable for prototypes or end-parts	
	• Builds strong, thin, complex parts with no need of additional supporting material • Certain applications require post processing • Can build molds and cores	
	• Complex geometries with high precision • Most profitable but future adoption may lag other 3DP • Requires supporting structures	

Metals Plastics Aerospace Automotive Industry
Ceramics Composites Healthcare Logistics Consumer Goods/ Retail

Although the technology has been around since the mid-1980s, its popularity has changed drastically over the last five to ten years (see Figure 2).

Fig. 2 – Technical development and important milestones of Additive Manufacturing[2]



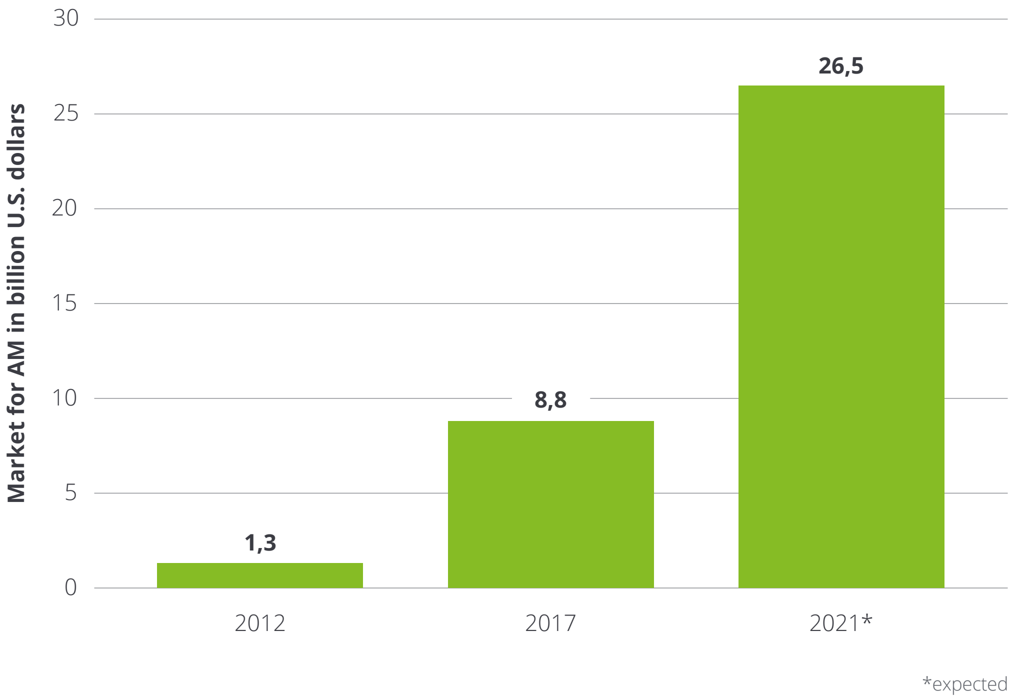


[2] Timeline of 3D printing
http://individual.troweprice.com/staticFiles/Retail/Shared/PDFs/3D_Printing_Infographic_FINAL.pdf

Disruptive manufacturing – The effects of 3D printing
https://www2.deloitte.com/content/dam/Deloitte/ca/Documents/insights-and-issues/ca-en-insights-issues-disruptive-manufacturing.pdf

Thanks especially to the expiration of important patents relating to AM, we have seen a wave of consumer-oriented printers with falling prices. The market grew annually by 47 percent from 2012 to 2017 and is expected to reach $ 26.5 billion by 2021 (see Figure 3).

Fig. 3 – Global market size of Additive Manufacturing from 2012 to 2021[3]



[3] Statista – https://www.statista.com/statistics/261693/3d-printing-market-value-forecast/

Potential

Increased interest in this technology is strongly correlated to the trend of decreasing product lifecycles, influenced by such factors as growing global competition with new emerging players, the drive for innovation due to saturated markets and changing customer demands. Additive Manufacturing is seen as a way to confront this challenge by significantly reducing time-to-market and opening up new opportunities for the economy and society (see Figure 4).

AM holds strong potential to revolutionize design and manufacturing processes and enhance functionality in parts and products.

Fig. 4 – Advantages of Additive Manufacturing with examples[4]

Advantages	Examples
Complexity and performance AM enables more complex and high performing geometries which are not possible with conventional methods. This supports the building of products designed for performance rather than for manufacturability	NASA redesigned an engine fuel injector and reduced 115 individual subcomponents to two subcomponents. The redesigned injector was able to fuel an engine that produced 20,000 pounds of thrust of up to 3,300°C while withstanding 1,400 pounds of pressure per square inch.
Time to market AM increases the flexibility for design innovations and redesign. Product modifications can be realized immediately and no time is needed for assembly, tool development, shipping or transportation	A manufacturer of educational laboratory equipment was able to print turbine wax mold patterns in 18 hours as a single component, in contrast to its traditional multi-tool process requiring 170 hours.
Cost reduction AM reduces the total cost of ownership due to lower inventories and fewer various machines and tooling. Less material for production is needed with reduced waste generation	A NASCAR race team adopted AM to produce prototype parts for wind-tunnel testing, the team was able to slash testing costs by 89 percent due to the elimination of scrap and lack of tooling creation.
Customization AM enhances product differentiation and direct-to-consumer relationships by creating individually customized and unique products without additional retooling or post-processing	Siemens has created over 10 million custom hearing aid shells using AM and claims they provide a better-fitting product that improves customer satisfaction.
Eco-friendliness AM creates a smaller environmental footprint than conventional methods due to its reduced mass, efficient use of resources and shorter supply chain	An aircraft manufacturer reduced the mass of an engine component by 4–7 percent and generated savings of up to 7,200 gigajoules of energy and 550 metric tons of CO_2-equivalent emissions per aircraft annually.

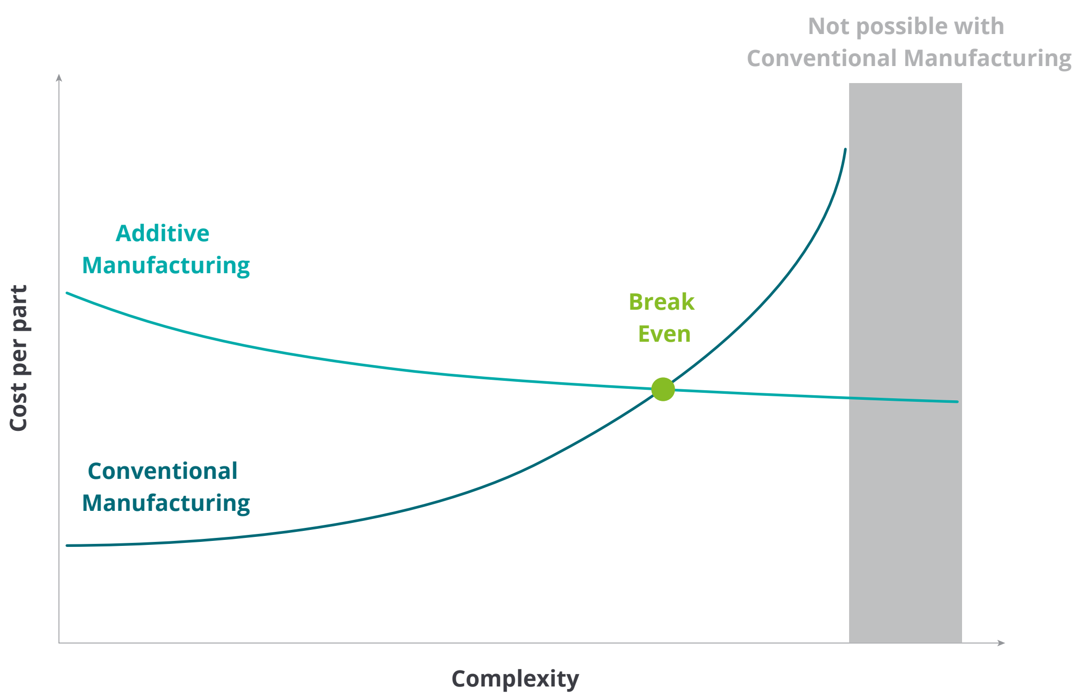
[4] 3D Systems, "Learn how turbine technologies cuts prototyping time and production costs by 90 percent with MultiJet 3D printing," http://3dprinters.3dsystems.com/turbine-technologies-multijet-3d-printing-webcast-lp-thanks-pdd/

"Wind tunnel testing with PolyJet or FDM parts," Stratasys, https://www.stratasys.com/it/applicazioni/rapid-prototyping/prototipo-funzionale/wind-tunnel-testing

Matthias Froelich, Insio: A new standard in custom instruments, Siemens, 2013, pp. 1–7.
3D opportunity for life cycle assessments – Additive manufacturing branches out
https://www2.deloitte.com/tr/en/pages/manufacturing/articles/additive-manufacturing-in-lca-analysis.html

The layer-by-layer approach gives manufacturers unprecedented freedom to create complex, composite and hybrid structures with substantial precision and control. Previously impossible geometries and shapes became feasible with this mode of production, sparking new options for design and manufacturing. Beyond shape, AM can help engineers deploy new approaches, structures and functions, along with novel materials that may improve functionality and performance. In comparison with conventional manufacturing (CM) processes such as casting, turning or milling, the economic benefits of AM increase the more complex the design becomes thanks to the flexibility in redesigns or design innovations. Complex geometries tailored to specific customer specifications that may not be possible with conventional methods can be built with less material and lower total costs (see Figure 5). What is more, mechanical components with moving parts can be printed in a single sequence, without any tooling, set-up or assembly required. Objects can also be built just in time where and when they are needed, reducing inventory, freight and waste.

Fig. 5 – Product complexity versus costs: Conventional versus Additive Manufacturing[5]



[5] https://www.fhnw.ch/de/die-fhnw/hochschulen/ht/institute/institut-fuer-produkt-und-produktionsengineering/additive-manufacturing

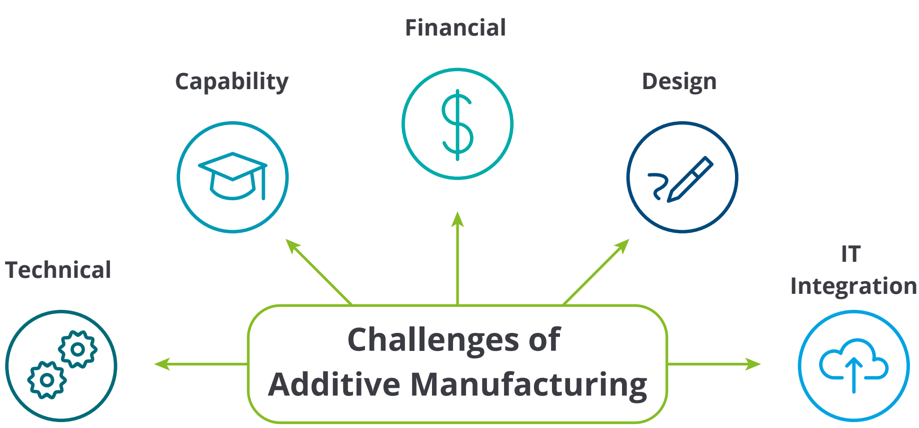
Challenges to scaled production

With the clear benefits of Additive Manufacturing in mind, whether or not these technologies achieve broader success will depend on how well the printed objects serve the intended use in the market. It is crucial that the unique ability to create such superior shapes and structures is also translated into useful products. At the same time costs during the entire product lifecycle must remain competitive.

Although AM was first used commercially in the mid-1980s to produce concept models, design or functional prototypes and visualization tools, more recent advances in printer and material technology have enabled AM to expand to applications such as factory tooling, spare parts and end-use products. AM is currently used primarily for low-volume parts production, but is also slowly becoming a valued part of production processes more generally. And yet, a recent study found that 63 percent of enterprise AM users deploy the technology for prototyping, while only 21 percent use AM for items that cannot be made with any other manufacturing technology[6]. That is, of course, if AM is being used at all. In some cases, engineers only use 3D printers to test out idle curiosities; in others, the AM machines are simply left in the corner to collect dust.

These numbers clearly indicate that there is still something preventing manufacturers from integrating AM technologies more generally into their manufacturing process. It shows that we still have challenges that must be addressed before AM achieves widespread adoption, particularly technical, IT, design, capability and financial challenges (see Figure 6).

Fig. 6 – Challenges of Additive Manufacturing



[6] Brian Burke and Pete Basiliere, "An enterprise architect's best practices for 3D printing," Gartner

Technical Challenges

As mentioned above, AM is mainly used for prototyping. But why is that? One of the reasons is surely that a lot of organizations and their engineers are still impeded by traditional design constraints. The further research required to overcome technical challenges is another reason for poor AM adoption in manufacturing companies. In order to push AM adoption beyond the purpose of prototyping, there are a number of technical challenges that need to be addressed, mainly in the area of materials and processing.

Currently, only a few materials can be processed within the required quality specifications, and there is still standardization necessary for those that can.

Material challenges

Materials for traditional manufacturing technologies have already undergone years of development in terms of both processability and the necessary product properties. In addition to this solid database of materials, the industry has defined material standards and specifications through globally accepted and used norms. With AM being a rather young technology, there is still a gap to close in terms of development, standardization and qualification of materials. The economic success of AM technologies depends on the degree to which manufacturers can ensure that properties of the materials used to make the required shapes or structures actually meet the industry's pre-defined and accepted norms or standards. Currently, only a few materials can be processed within the required quality specifications, and there is still standardization necessary for those that can.

The overarching goal must therefore be the development and availability of a solid database with information on the mechanical and thermal properties of AM materials. There is still no set of common standards, e.g. fire resistance of certain materials and parts, or of special requirements for certain industries. Development of globally-defined standards must be a top priority.

But the challenges of AM materials go even further. Looking at AM from an environmental point of view, one of its biggest advantages is recyclability, i.e. the use of surplus material for the next print. While most of the metals used in AM can be recycled, many polymers cannot. Those polymers that can be recycled suffer from a potential quality loss. Further research is needed if we intend to fully meet sustainability goals, even as AM manufacturers have started to cooperate with chemical companies to accelerate the development and standardization of new materials.

Procedural manufacturing challenges

In today's state-of-the-art production lines, processes are highly synchronized and timeframes for production, changeover or product handling time have been reduced to a minimum. The whole value creation process is precisely timed and based on the reliability of each machine integrated in the process, placing high demands on AM technologies. While AM promises to introduce flexibility into conventional manufacturing processes, reliability is essential. Today, these technologies are quite costly and still lacking in terms of process stability, part quality or reproducibility. Production throughput speed is also rather low compared to conventional manufacturing technologies, though in some cases – especially for high volumes – by only several seconds. One could argue that these longer processing times are justified due to the fact that printed products do not require subsequent assembly. Moreover, the extra time for exact machine calibration in today's AM technologies affects changeover times for different product types (with different materials) and complicates efforts to synchronize AM technologies with conventional technologies in the production process.

Even though AM makes it possible to print an entire product without any further assembly required, most manufacturers demand an additional surface finish to meet high quality specs or surface requirements. Where the surface quality of parts produced with AM is inferior to those produced conventionally, further processing is needed to comply with the required tolerances for the surface finish. To guarantee product quality and tolerance compliance, inspection and quality assurance are essential. Inline quality control is still relatively new to AM technologies and presents a barrier for manufacturers to implement. While some very complex and unconventional shapes are possible with AM, manufacturers struggle to deliver robust quality without the appropriate metrological tools and methodologies for AM.

Even though the above-mentioned limitations are temporary and likely to diminish with technological progress, near-future connectivity in the manufacturing process remains a challenge for AM technologies. It will be absolutely essential to master issues such as optimized data preparation, real time process monitoring and control before we can fully integrate AM technologies into modern manufacturing lines.

IT Integration Challenges

Integrating with supporting 3D printing software

The entire process of customer-specific AM is largely manual today. In other words, a CAD model is designed, sliced for 3D printing and then transferred to the printer using, say, a USB stick with the files. The process is monitored via a display on the 3D printer, while quality checks run manually after the print is completed. This is akin to the manual steps often seen in the post-processing of 3D printed parts.

This manual labor is justifiable to some degree for early use cases of AM. In prototyping, with a limited number of parts produced and little need for extensive data collection, it was not necessary to closely integrate the 3D printer into supporting software solutions. Now that the application landscape is shifting towards mass production, it is becoming increasingly important to reduce costs for items such as manual labor through integration. Some vendors are starting to provide APIs that connect with the 3D printer, but these are largely not standardized or widely used, making the integration task challenging and costly.

Integrating into the digital enterprise

Modern factories have taken big leaps forward in terms of digitization, positively impacting on both cost and cycle time. The scope of digitalization is not, however, limited to the shop floor itself; it covers the enterprise's entire value chain. Typically, every step from the supply chain to the warehouse and the shop floor to goods issue will be digitized in some way. This digital transformation has played a major role in the efficiency gains we have seen over the last two decades.

Unfortunately, the IT solutions in question are not usually built to track single parts, but rather types of parts – such as SAP ERP, which can calculate the quantitative yield of a specific material. While suitable for the mass production of identical parts, these solutions are unable to conceptualize replaceable parts when they are individually produced – one of the major drivers of AM. For example, SAP ERP may consider a number of parts with minor customizations as a single material, but if no distinction is made at goods issue before shipping, a customer might receive someone else's customized part.

That means that resource management tools need to be adapted accordingly, e.g. by tracking single parts through the production cycle as well as in the warehouse. In many cases, this is not a simple adaptation of the software solution, but a conceptual shift that has major implications for the data architecture.

The digital thread

In order to make the most of the flexibility provided by AM, we need to establish so-called digital threads. The digital thread describes the digital data recorded and consistently expanded throughout the entire lifecycle of the part. This means collecting data from each stage of the design and manufacturing process, through to the final decommissioning of the part.
This type of solution could also alleviate many of the technical challenges mentioned above. As quality records are maintained long after the part has left the factory, quality issues later in the lifecycle can still be traced back to the design features and previous quality results, enabling a better understanding of the way materials and specific design features behave in the long run.

There is still a long way to go for many manufacturers to make this scenario a reality. The software modules already available on the market are unable to improve the level of automation in terms of quality. They look at Additive Manufacturing in purely economic terms (e.g. tracking only target values such as "short construction time" or "high packing density" instead of features relevant for production or quality assurance) and require a high degree of manual operation.

The digital thread describes the digital data recorded and consistently expanded throughout the entire lifecycle of the part.

Design Challenges

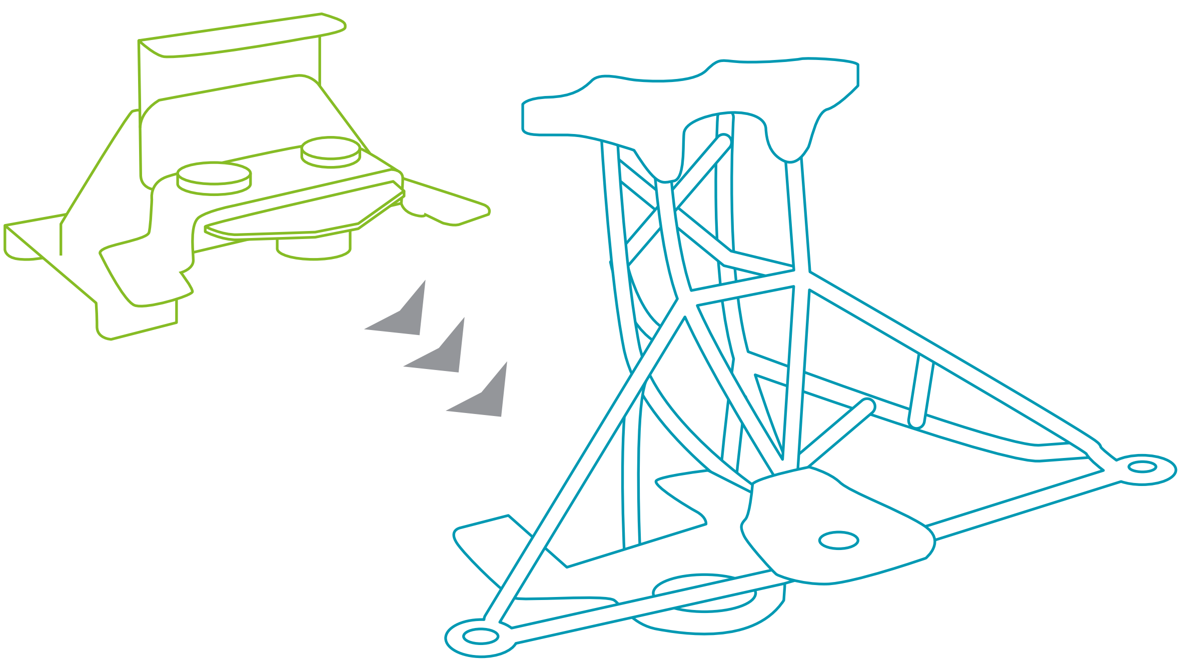
What is the right approach?

In general, there are two possible approaches to start transitioning to integrated AM. Most companies are trying to identify existing products that could move from conventional manufacturing to Additive Manufacturing. It is extremely difficult to generate a positive business case for serial production in these cases.

While customer requirements naturally define the product features, the impact of the chosen manufacturing process on the product's design is not insignificant. There are different design principles for milling, molding, welding, etc. that define the form, look and feel of a product. Designers and engineers have to consider, for example, the minimum wall thickness and rounded edges for molding. Over the years, product design has been adapted and optimized according to design principles of different manufacturing processes. Simply reproducing the product with AM is not efficient.

The second approach rethinks the entire product structure in order to take full advantage of AM's capabilities. The challenge is to identify the part and assembly designs determined by the current manufacturing technology and consider whether AM can improve performance. As AM makes it possible to create geometries that are not feasible with conventional manufacturing methods (see Figure 7), design freedom increases. It is down to designers and engineers to adapt to the AM process and factor the new capabilities into the entire product development process.

Fig. 7 – Exemplary optimization of a mounting bracket[7]



[7] Source: Additive Serienfertigung, 2018, R. Lachmayer, S. Kaierle, R. Lippert, Berlin

What are the design principles?

When it comes to AM, engineers still consider the same design constraints that complicate conventional manufacturing. Rather than shifting to an entirely new approach to design, they revert to well-worn, comfortable design paradigms – especially engineers who may have spent much of their careers working through a conventional set of processes. In conventional manufacturing, there are clear roles for each stage of design and production. There are individualized tasks and extended design workflows for specialized tasks, each with multiple iterations for various design constraints. The design is modified for each discipline based on its discrete function, e.g. fluid engineering, electrical engineering or thermal engineering, to optimize features for its specific function while still considering manufacturability.

AM totally reframes the design process. Instead of a number of specializations and discrete tasks that were formerly performed by various engineering functions, AM takes a big picture view with cross-functional perspectives and multiple considerations. The result is a condensed, collaborative and less linear process with fewer design steps. Roles can be fuzzier, and designs can theoretically move straight from computer models to the printer with a few stops to adjust for manufacturability and cost, removing entire stages of the workflow.

Thanks to this new design framework, designers may find it hard to realize all of the design freedom unleashed by AM. The changes enable them to think beyond traditional design requirements and paradigms to concentrate purely on performance, demanding that they widen their perspective further still and embrace entirely different manufacturing approaches.

Moreover, in contrast to traditional manufacturing methods, there are no uniform norms and standards for design using AM. Each manufacturer of AM machines provides their own technical recommendations, but they are not yet mature enough in comparison to conventional methods. To date, there is no proven standardized framework for AM to lean on and less profound knowledge about the limitations of the process. We need to develop new design methods and tools and create a database of standardized features for topology optimization.

Capability Challenges

A successful transition to AM will require new engineering and management skills to exploit the full benefits of this technology, although we are currently facing a significant skills gap. It is difficult to find a well-trained and skilled workforce that are capable of applying 3D printing to real-world production. Even though current engineering graduates may have learned about the technology, it is unusual to find potential recruits who understand the holistic capabilities of the technology. Additive Manufacturing is not a technology for specialist technicians like welding, for example, but rather a field for generalists able to combine such different disciplines as mechanical, fluid and material engineering. As a result, most of the workforce is still too unfamiliar with the different materials and the requirements of the design process to take full advantage of the potential offered by AM.

The current shortage of talent calls for new education initiatives to deliver a skilled, capable and adaptable workforce. However, without any norms or standards for AM design principles, German industry has been unable to establish uniform apprenticeships or study programs as of yet – to say nothing of global players.

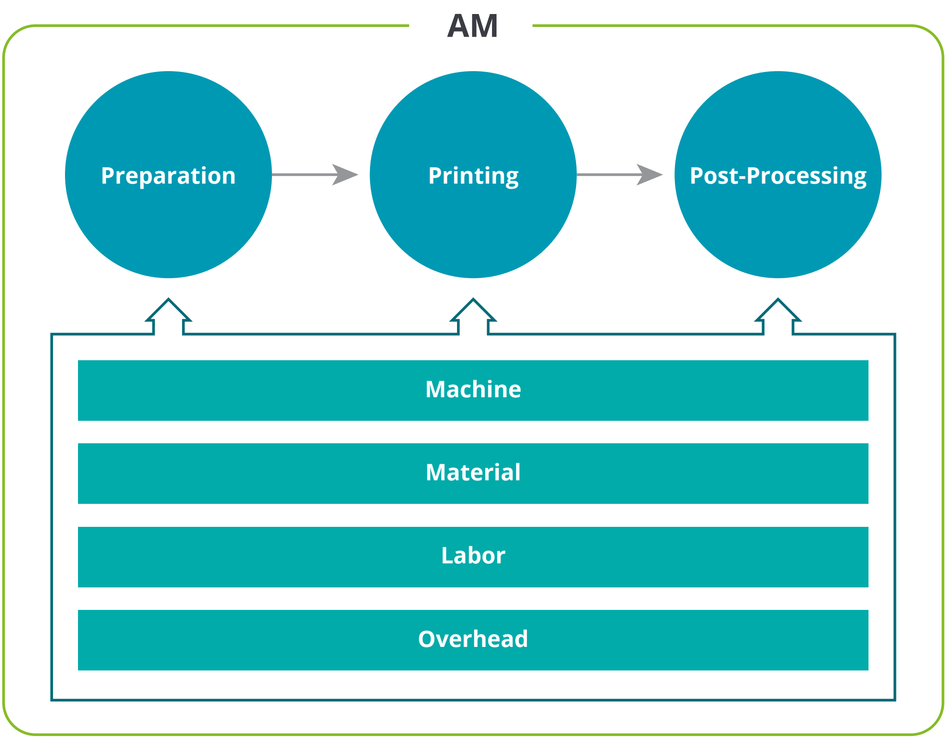
Far too few companies are promoting trainee programs or continuing education that take a multidisciplinary, integrated approach. Existing courses for design, engineering and management related to production and manufacturing do not have a system to deliver the necessary skills and knowledge for the effective deployment of AM technologies. Moreover, the programs focus on developing experienced specialists rather than training new AM experts. An efficient transition to AM requires a workforce that is capable of working in cross-functional teams and using modelling software and 3D scanning systems. They must understand the specifications of different processes including post-processing, machines, applications and materials in order to evaluate the implications of AM on the entire value chain and business model.

Financial Challenges

Identifying the business case of disruptive technologies is a significant challenge as well. When we think back to the launch of the first iPhone, we understand that it changed the game not because of its initial technology. Top-line phones from other companies had more memory, better cameras and faster mobile connectivity. The business case was rather the result of the full extent of the product.

In general, the cost factors for conventional manufacturing relate to machines, materials, equipment, tooling, labor and overheads such as energy and space. For Additive Manufacturing, the cost model is structured as a series of workflow steps: preparation, printing and post-processing, where each step has its own cost factors (see Figure 8). These factors are different than those of conventional methods. There are usually no investments needed for mold tooling and the equipment can be used for a variety of purposes.

Fig. 8 – Cost model of AM

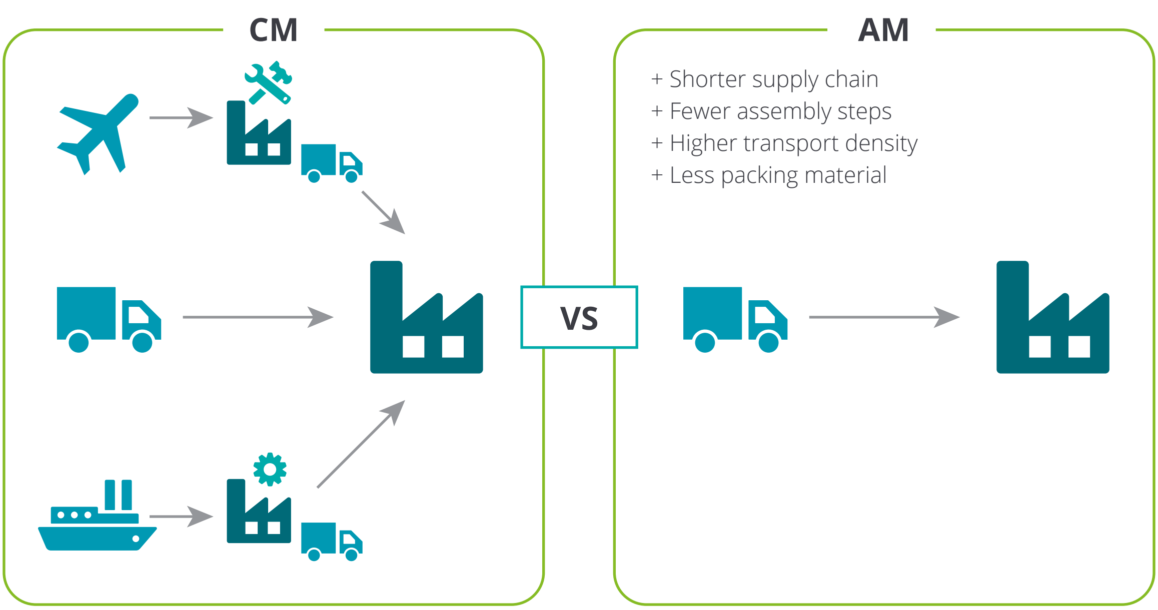


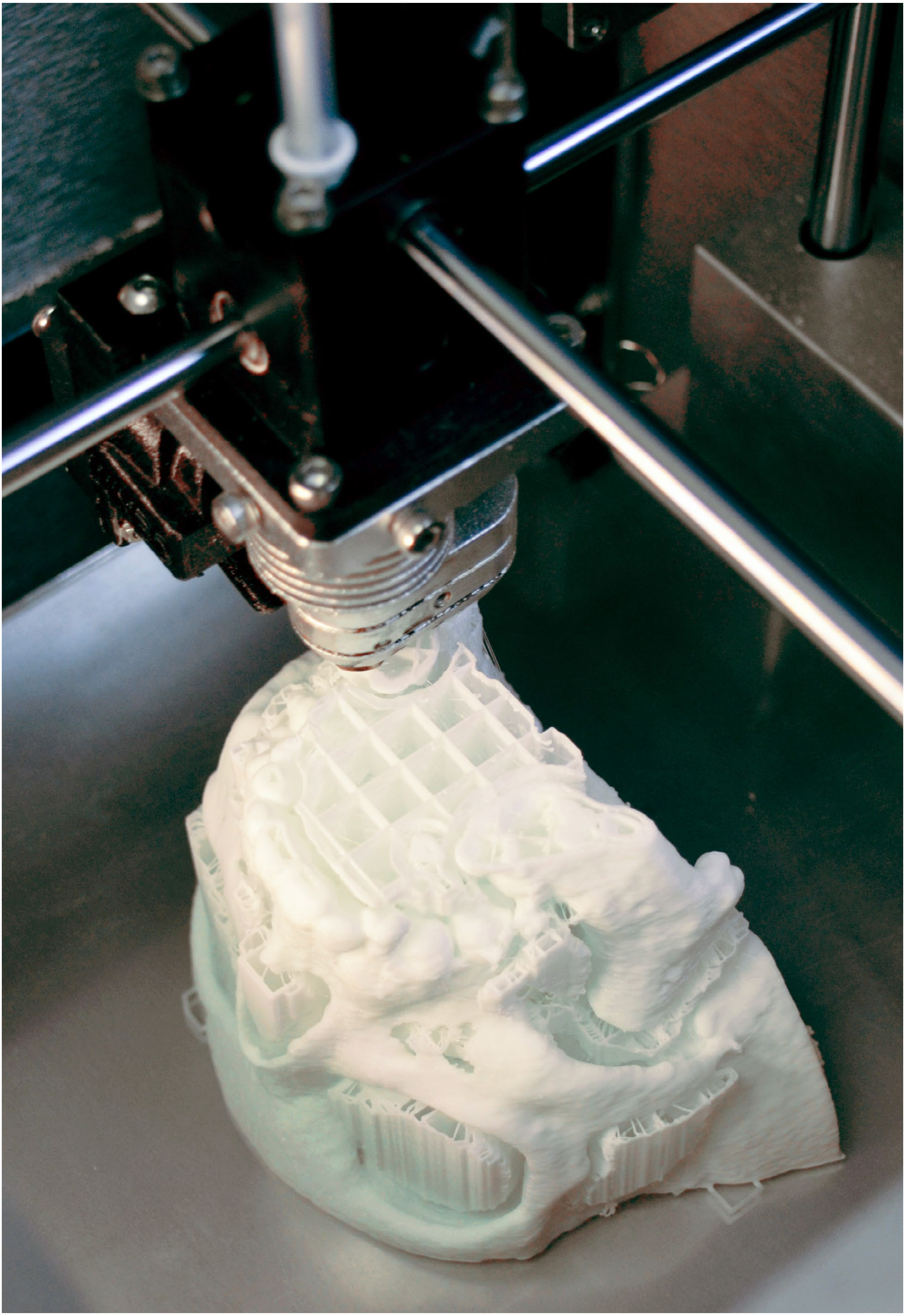
It's just the tip of the iceberg
Even if manufacturers achieve a detailed analysis of the production costs, it can only be of limited value. These figures may not reveal the full extent of the financial and environmental potential offered by AM that can add dramatic value for companies and their customers. Additive Manufacturing impacts the entire supply chain and product lifecycle. The variety of complex factors and their impacts are rarely considered for making a business case. It is necessary but difficult to analyze the overall impact and evaluate AM adoption from a scale perspective across a supply chain.

Many analyses are limited when it comes to quantifying the environmental impact. They focus purely on criteria such as standby and in-process electrical consumption. Aspects such as waste flows, resource consumption or emissions generated are rarely considered.

Additive Manufacturing can be more eco-friendly than conventional methods thanks to factors such as reducing material waste and avoiding environmentally hazardous materials like caustic cutting fluids. This impact is rarely outlined in these analyses. The emission, fuel and energy savings for shipping and transportation along the supply chain also have an impact (see Figure 9). In addition to the direct impact on manufacturers, there are also indirect factors. As already outlined, AM can produce customized products and lighter parts with better performance. In terms of energy consumption during operation of products with long lifecycles like airplanes, lightweight design can reduce fuel costs significantly. Customized, economical products are more attractive and increase demand and sales, but how can we factor these impacts representatively into a calculation for the business case?

Fig. 9 – Exemplary supply chain of CM and AM for the production of a fuel injector for aerospace





Conclusion

Additive Manufacturing opens up new opportunities for design and manufacturing across different industries. Compared to conventional methods, more complex structures and geometries can achieve customized design, greater efficiencies, higher performance and better environmental sustainability. As a result, the technology is seeing increased adoption beyond prototyping and tooling into end and spare part production.

Consequently, AM has an important role to play in the range of manufacturing methods. Companies can deploy to evolve their products in response to market demands. And as the technology continues to improve, AM changes from a disruptive technology used only by innovators to a common method for core production.

Widespread, scaled adoption for such products as end-use parts will, however, require overcoming a variety of challenges faced today:

- Technological challenges in terms of materials, process implementation, post-processing and quality assurance
- A lack of IT standards and a digital thread through each stage of the design and manufacturing process
- The shortage of well-trained and skilled technicians familiar with the technology and capable of applying 3D printing
- The rigid adherence of designers and engineers to established design principles with constraints
- A limited consideration of factors and impacts for business case calculation

Four Step Approach to overcome AM Challenges

In order to overcome these challenges, companies can follow a four-step approach (see Figure 10):

1. **Evaluate whether an Additive Manufacturing solution fits in your organization** and justify the need for it. Identify which products possess characteristics that would benefit from using AM and determine its feasibility as a manufacturing technique for these products. These characteristics include system complexity and a need for complex geometries or customization. Analyze all challenges which must be addressed.

2. **Calculate a business case** for using AM in the manufacturing process. This business case should examine impacts to the manufacturing process associated with the use of AM, including a reduction in assembly steps, scrap and inventory, as well as the elimination of tooling and potentially reduced lifecycle costs. These potential benefits should be weighed against any increased cost of materials and investment in part or product redesign.

3. **Develop a roadmap** for implementation that outlines expectations, capabilities and timing as well as measurements to meet the challenges. Pilot the solution to a targeted area and then scale the solution to the broader organization.

4. **Generate an organizational shift** to Additive Manufacturing and identify change champions inside the organization to help reach a critical mass of adoption. Look outside your company to identify partnerships as part of the AM ecosystem.

Fig. 10 – 4-step approach for effective AM implementation

Being an AM beginner and having these factors in mind, companies have the chance to learn and grow quickly, gaining a competitive edge in the continued expansion around the disruptive power of AM.

At Deloitte, we can offer manufacturers a holistic view of Additive Manufacturing with solutions from a single source. Our supply chain and manufacturing operations practices cooperate closely with our technology teams in order to cover top line issues such as processes and supply chain management, while simultaneously penetrating in-depth topics such as IT integration, manufacturing execution system and product lifecycle management.

Deloitte helps companies understand and address the opportunities and challenges associated with introducing Advanced Manufacturing technologies to impact business performance, innovation and growth. Our insights into AM allow us to help organizations reassess their people, process, technology and innovation strategies in light of this emerging technology.

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