In collaboration with
ETH Zurich and Fraunhofer

An Additive Manufacturing Breakthrough: A How-to Guide for Scaling and Overcoming Key Challenges

WHITE PAPER
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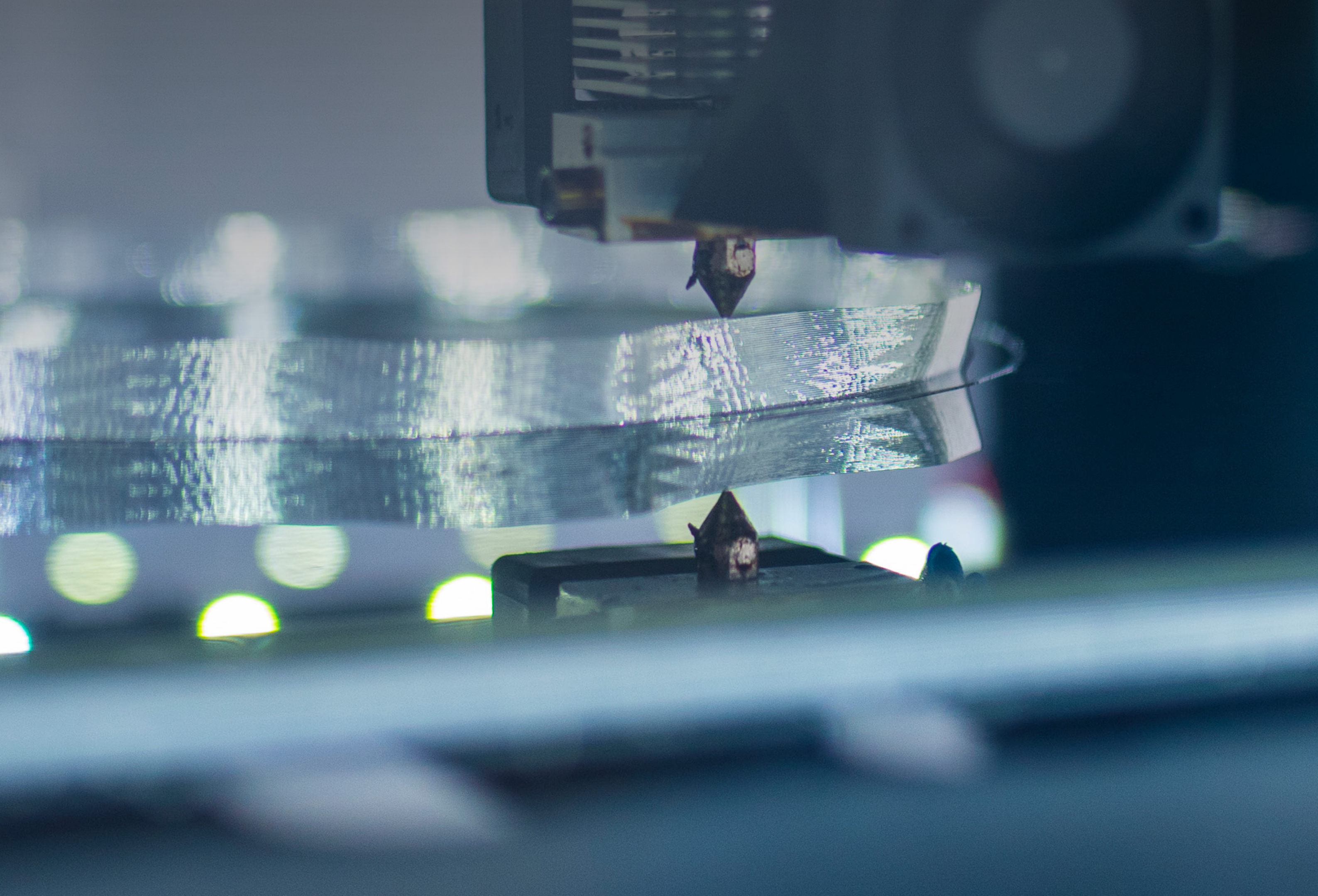

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Contents

Foreword

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For more than a decade, manufacturing leaders have seen cycles of hype associated with additive manufacturing (AM). Although not all predictions and forecasts have become reality, the industrialization of AM has passed through different waves, yet it still manages an average yearly growth rate of 20%. The industry as a whole is subject to an ongoing rationalization, with AM original equipment manufacturers (OEMs) going public and end users becoming more experienced with regard to the opportunities and limitations of the technology.

Recently, the potential of AM to play a significant role in the future of manufacturing has been underlined again within the context of the COVID-19 pandemic. When the entire world came to a standstill and healthcare systems found themselves overwhelmed and unable to cope with the skyrocketing demand for critical items such as nasal swabs and ventilator components, the AM sector was able to rapidly pivot to bolster these supply systems. In doing so, manufacturing leaders who had previously dismissed AM as either too expensive or too immature to be useful at an industrial scale once again became curious to understand what the technology is truly capable of today and how it might be used to make their own manufacturing systems more resilient, flexible and adept at responding to future shocks.

It was with that in mind that the World Economic Forum in collaboration with ETH Zurich[1] and three Fraunhofer Institutes (IGCV, IPT, IAPT)[2] made it their task to research the *real* story of AM, by speaking with manufacturing leaders from around the world and across different industries. This effort enabled us to move away from the hype and define a new return on investment (ROI)-based narrative of the industrialization of AM.

The aim of this white paper is to help senior industry executives better understand how they can leverage AM to realize more resilient, inclusive, flexible and sustainable production systems – creating and delivering value for companies, society and the environment – and to incubate new collaborations and partnerships by mobilizing the global manufacturing community.

Executive summary

This white paper was created by the World Economic Forum in collaboration with ETH Zurich and Fraunhofer IGCV, IPT and IAPT to assess the current state and future of additive manufacturing (AM) at industrial scale. The report is informed by in-depth interviews with AM original equipment manufacturers (OEMs), materials manufacturers and industrial end users, alongside further primary and secondary research to accurately convey the true potential of AM. The goal is to provide manufacturing companies with a realistic yet cutting-edge understanding of what AM can deliver today, and why some are achieving that potential while others are not, as well as the most probable near-term future production scenarios we can expect and what needs to happen to help accelerate their deployment.

This paper shows that despite the greatly improved maturity of AM, potential roadblocks can still be found along the whole value chain – including the fields of technology, organizations and ecosystems. With the help of four best practices and three real-world case studies, it highlights how those challenges can be overcome today. The case studies reveal that current key opportunity drivers can be found within the digital process chain, in new AM materials, in certified supply chains and in the application of novel business models. The future industrialization of AM is discussed in relation to potential production scenarios, key enablers and solutions. The analysis shows that a joint step towards industrialization of the overall AM process chain is necessary to foster sustained and sustainable growth of the AM industry. To facilitate this process, the report spotlights seven overarching themes in a call to action, addressing detailed statements for stakeholders in the AM ecosystem. Political decision-makers and C-level representatives are invited to orient themselves towards supporting this call to unlock sustainable growth for the AM sector.

1

Current and future challenges of AM implementation

While the technological maturity of AM has been demonstrated in specific industries, individual firms still struggle with its adoption and implementation at industrial scale. Companies underestimate the extent to which the adoption of AM is first and foremost a learning process that involves the entire value chain and requires specific AM expertise that needs to be acquired. Throughout this learning process, a wide range of challenges may hinder the progress and success of implementation. These include roadblocks related to technology, organization and the ecosystem in which manufacturing companies operate.

Based on the interviews conducted for this study and research insights, the following list has been compiled of the most relevant challenges to AM adoption and implementation (see Table 1).

TABLE 1

Potential challenges to AM adoption by area

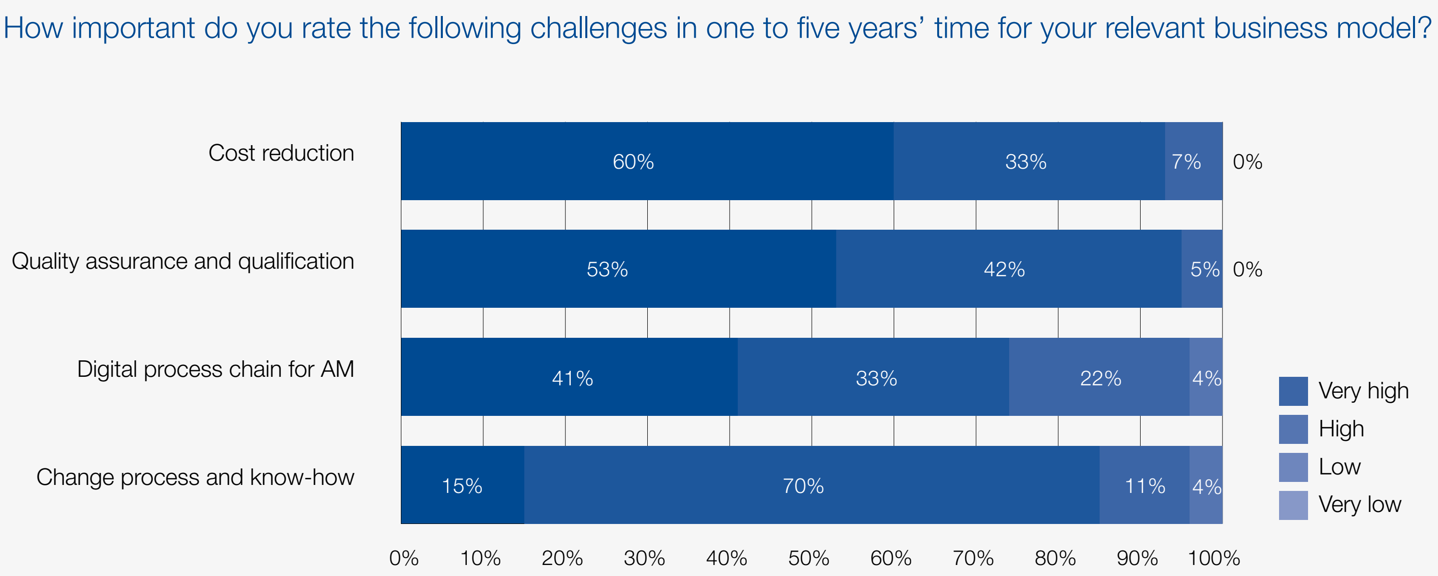
Area	Potential challenges to AM adoption
Technology-related challenges	– Limited process predictability and repeatability – Material availability still limited – Need for post-processing with high resulting costs – High cost of investments, operations and maintenance – Few procedures to certify the produced parts
Organization-related challenges	– Lack of clear AM adoption strategy at firm level – Inability to identify value-adding applications – Lack of adapted business models that tailor to AM potentials – Lack of accurate cost-calculation models – Uncertainty about ownership of digital designs that leads to unclear product protection – Limited knowledge of AM technology and design – Lack of highly skilled AM personnel as dedicated educational tracks are missing
Ecosystem-related challenges	– Unstandardized data transfer that leads to insufficient accuracy and quality of design files – Lack of an integrated digital process chain from designer to machine – Customers not yet familiarized with AM parts (shapes, materials, surfaces, haptics) – Lack of standards and qualification procedures for regulated industries

Source: Table adapted from Omidvarkarjan et al. (2022),[3] items informed from literature and interviews

To better understand the implications of those roadblocks, interviewees were asked to rate the future importance of the individual roadblocks. The results of this rating are displayed in Figure 1 below. It shows that costs will remain a key challenge, ahead of qualification, digital processes and knowledge.

FIGURE 1

Assessment of future challenges for AM



Source: Fraunhofer surveys and interviews

Today and in the foreseeable future, the production costs of AM parts are a principal obstacle to adopting AM. Some experts point out that this refers not only to machine and material costs, but that perceived lack of robustness and quality also have a significant impact on costs. Both factors lead to high quality-assurance costs after the AM process. Complex geometries of AM parts, small lot sizes and other particularities of AM make it challenging to post-process and automate the production. As a result, post-processing accounts for a significant share of the overall part costs.

Lack of defined standards in regulated areas such as aerospace, rail, automotive or the medical industries is slowing the growth of the AM market. Standardization is a bottleneck, as AM implementation requires companies to clarify uncertainties, ensure liability and pass approval processes. In this context, the certification of AM parts and the qualification of production is seen as a key challenge for the next 10 years by the vast majority of surveyed industry experts.

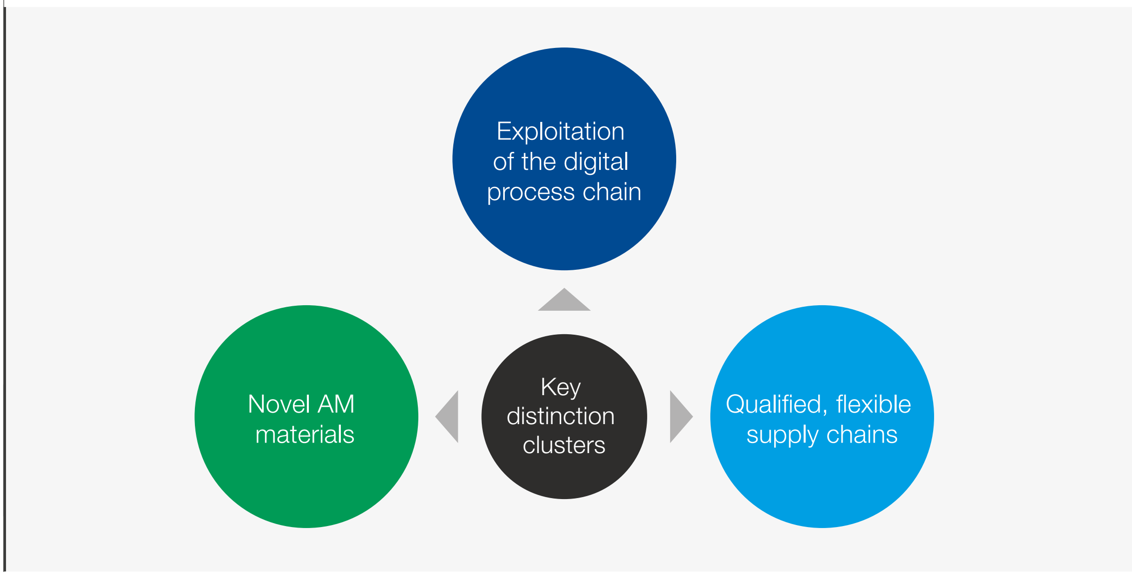
AM is often described as a digital process. Particular digital production scenarios such as mass customization require an efficient digital backbone. However, talking with today's industrial AM experts showed that the interruption of the digital process chain is an ongoing challenge that is expected to be resolved slowly. The interconnection of software from one supplier to the next along the process chain is lacking, leading to the introduction of intermediate steps that reduce quality. In addition, the information generated along the process chain is not consistently available or shared.

Another issue highlighted by interviewees is that companies need a high level of know-how to develop suitable applications and implement additive manufacturing in their businesses. For example, the current cost-competitive parts need to exploit the AM advantages. On the long-term perspective, over five to 10 years, survey participants expect this challenge to become less relevant. This can be explained through continuous improvements in knowledge and skills within the industry and by students entering the workforce after following an AM curriculum.

2 Current opportunities enabled by AM: case studies from the industry

Although the aforementioned challenges and roadblocks may seem daunting at first sight, many successful implementations of AM in real-world products underline the fact that, overall, the opportunities created by AM greatly outweigh its limitations and drawbacks.[4] To showcase the current potential of AM, this paper contains a number of highly advanced and innovative implementation case studies. These real-world examples have all been validated with a sustainable business case – underlining the fact that AM is already suitable for value-adding applications. Through a comprehensive analysis of the case studies, three key characteristics of highly advanced AM applications have been identified (see Figure 2). Together, they enable firms to create novel ways of capturing value, such as through the application of new, digital business models. The following section presents these three clusters together with their corresponding case study.

FIGURE 2 **Three key distinction clusters of highly advanced AM applications identified in this study**



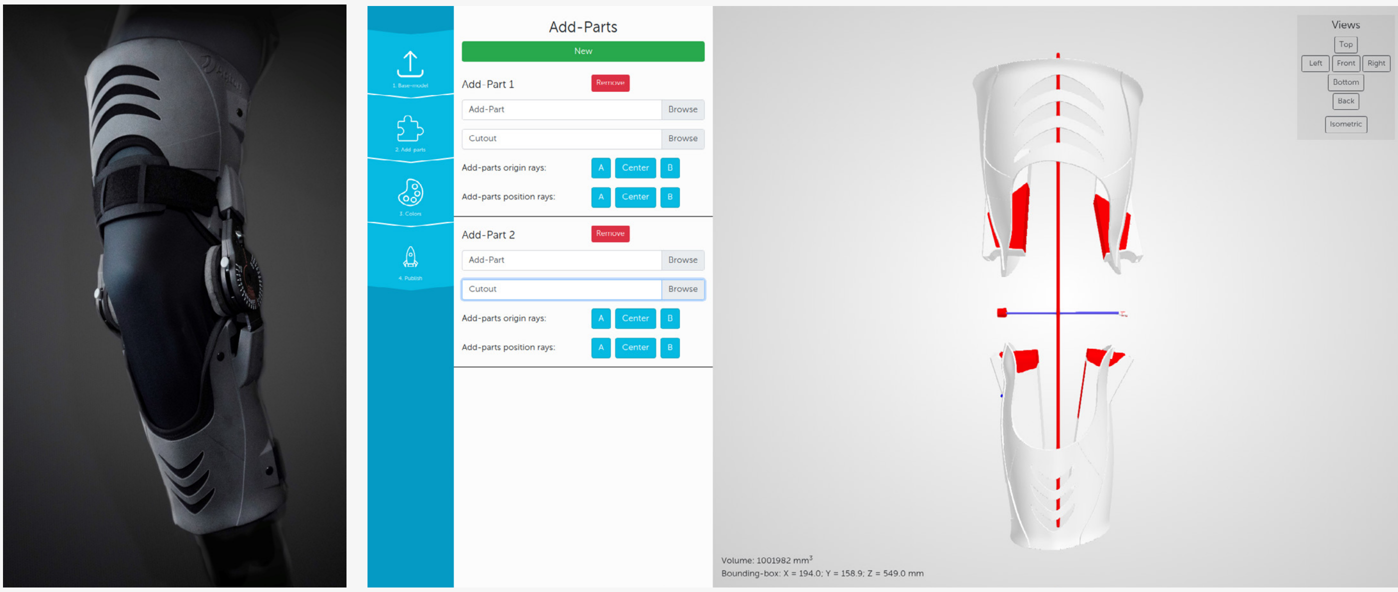
Source: Inspire

2.1 Exploitation of the digital process chain

While at heart a manufacturing process, AM is in many ways more of a technology platform. Due to its digital nature, it is compatible with a wide range of other technologies from the Industry 4.0 context, including, for instance, data-driven design, artificial intelligence (AI) (e.g. for real-time process monitoring) and digital supply chains. This unique capability is mainly enabled by the digital thread that spans the AM process chain. Along the entire product life cycle (design, manufacturing, supply chain, validation, in-use, service and end-of-life), data can be captured to improve the performance, efficiency and cost of an AM application.

The following case study by Trinckle[5] and Aqtor![6] is an ideal example that showcases how a digital process chain can be leveraged to build highly advanced AM applications. Conjointly, the firms developed an automated design platform for 3D-printed orthoses. The design platform covers a wide range of automation levels such as simple parameter manipulation and more sophisticated features such as automatic fitting of AM orthoses to 3D scans of patients. The platform has been in use since 2019, with three products having been implemented and many more underway. The most mature example is a knee brace that has been produced more than 350 times already. In the near future, the platform could be extended by integrating smart, connected sensors into the AM orthoses, enabling the acquisition of data while the products are in use. This would create novel opportunities for customer interaction; for instance, in the form of adapted training plans. From a business perspective, the implementation of the design platform led to a reduction of labour as recurring design work could be automated. Depending on the product, this reduction ranges from 40% to 60%.

Overall, the case study is an ideal example to illustrate how the digital process chain of AM creates significant benefits through the automation of individual process steps. From a business perspective, this opens up a wide range of new opportunities with regard to how products can be sold and how OEMs interact with their customers.



Note: Left: automatically designed AM orthosis. Right: Screenshot of the design automation tool

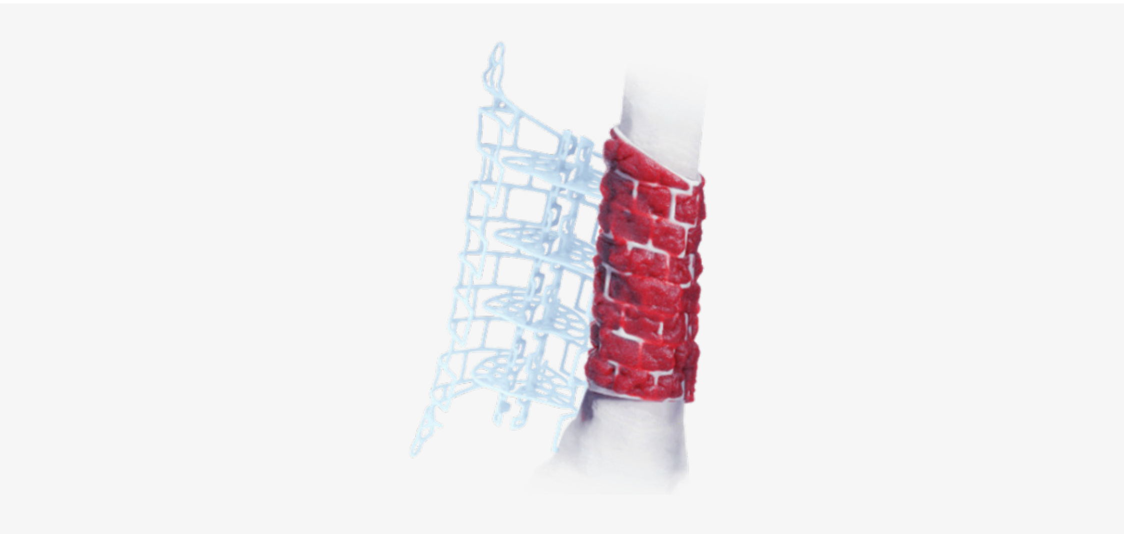
Source: Aqtor! & Trinckle

2.2 Novel AM materials

In recent years, many novel AM materials have been developed. This is welcomed, since previously the low range of available AM materials was one of the major barriers to implementation. The development of novel materials specifically for AM has led to significant benefits such as reduced costs, increased performance and new applications.

The following development by Johnson & Johnson (J&J)[7] illustrates how novel AM materials enable highly innovative applications. J&J developed and launched a patient-specific implant to treat certain medical conditions. It comprised an individualized cage that acts as structural support for the bone-healing process. Based on a computed tomography (CT) scan, an individualized design is created within 24 hours. After approval by the surgeon, the part is manufactured in a central facility and delivered within days to the point of care. The highly complex structure is produced with a material blend based on polycaprolactone (PCL) in a selective laser sintering (SLS) process. This polymer is bioresorbable, meaning that it is fully absorbed by the body over two to four years. To improve the integration into the surrounding bone structure, the implant is coated with calcium phosphate, which is very similar to the material present in human bones. The combination of the novel AM material with an individualized design and special post-processing provides multiple benefits compared to conventional existing solutions. These include faster bone remodelling, greater final bone volume and increased torsional strength. More than 90 implants have so far been installed successfully.

Overall, this case study underlines the potential of novel AM materials. By combining them with a suitable manufacturing process and digital process chain from design to fabrication, firms can provide vastly advanced AM applications with increased functionality and better availability at a competitive cost.



Note: Individualized AM implant for critical-sized segmental bone defects

Source: J&J

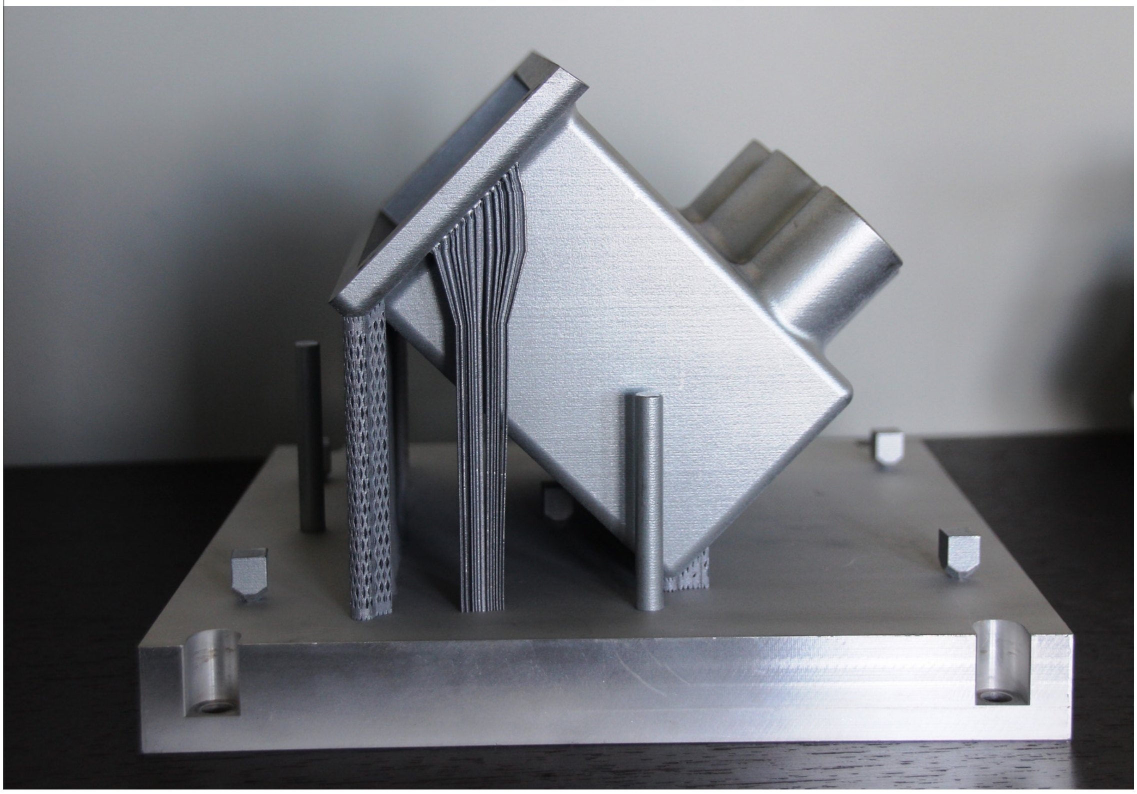
2.3 Qualified, flexible supply chain networks

Besides its freedom of design, AM's unique supply chain characteristics have been one of the major motivators for organizations to adopt the technology. This includes, for instance, the capability to produce items in single lot sizes without greatly increased cost, and the ability to have decentralized production close to the point of use. As seen at the beginning of the COVID-19 pandemic, AM can also create more resilient and flexible supply chains, which are able to step in when conventional manufacturing is not able to deliver.

The following case study of Deutsche Bahn (DB)[8] and TÜV SÜD[9] illustrates how such an AM supply chain can be established. As Central Europe's largest railway company, DB runs a large fleet of heterogeneous vehicles for passenger and cargo transportation. Maintaining those vehicles and ensuring the constant availability of spare parts is a complex task, as the vehicles and infrastructure were produced by different manufacturers over a long period of time. In this context, AM represents a viable alternative, as it enables the rapid and economical production of single, hard-to-source components. Nevertheless, one major challenge regarding AM spare parts is related to the strict regulations of the railway industry.

To address this challenge, DB teamed up with TÜV SÜD to develop a certification scheme for suppliers of AM spare parts and end-use components. A main cornerstone of this programme is an audit of the supplier's internal processes and quality assurance measures to ensure a sufficient level of quality and reproducibility. To date, more than 25,000 spare parts and end-use components have been manufactured at DB and its suppliers, including parts made from both metal and plastics, with the major share being non-safety-critical components. The introduction of a common quality assurance standard and certification scheme has led to multiple benefits, reducing the overall qualification effort for DB thanks to the standardized procedure. At the same time, certified suppliers also reported that the audit helped them to optimize their internal processes.

The case study therefore highlights the importance and potential arising from the standardization of AM processes. It acts as a prerequisite for more flexible and resilient supply chains, which enable advanced production scenarios such as on-demand or decentralized manufacturing.



Note: Motor mount manufactured as spare part with AM

Source: Deutsche Bahn

3 Strategies and best practices for the adoption of AM

On the basis of case studies and expert interviews, we have compiled four practical recommendations for firms interested in the implementation of AM at scale (see Figure 3).

FIGURE 3 **Best practices for the adoption of AM**

Source: Inspire

3.1 Implement in iterations

The case studies show that the implementation of AM requires a wide range of competences. With this in mind, AM adoption can be seen primarily as a learning process in which firms are required to develop their AM knowledge through validated learning.[10] This steep learning curve can be managed by applying an iterative, validated learning approach. Firms are therefore advised to start the AM adoption process with applications of very limited complexity. After completion, the firms can move to more advanced applications, gradually increasing their AM competence and level of adoption.

3.2 Pull, don't push

AM adoption is typically a highly capital-intensive process, since it requires investment in machines, education, research and development.[11] To increase the likelihood of successful implementation, AM applications should therefore be primarily motivated by a valid customer need and convincing business case to create a self-sustaining adoption environment. This market-pull strategy is in stark contrast to a technology-push approach, where organizations attempt to showcase AM's technological capabilities in overly complex demonstrators, while serving no or only limited business value. The big hurdle in AM technology is no longer the technical feasibility but the cost-benefit ratio and finding a suitable business model.

3.3 Collaborate to complement

As mentioned earlier, the implementation of AM typically requires a broad range of competences along the entire AM process chain. For an individual firm, it may be very hard to cover all of those aspects internally, especially at the start of the adoption process. To address this issue, firms are encouraged to collaborate with external partners such as research institutions, contract manufacturers or service providers to fill competence gaps or lack of expert skills and knowledge.

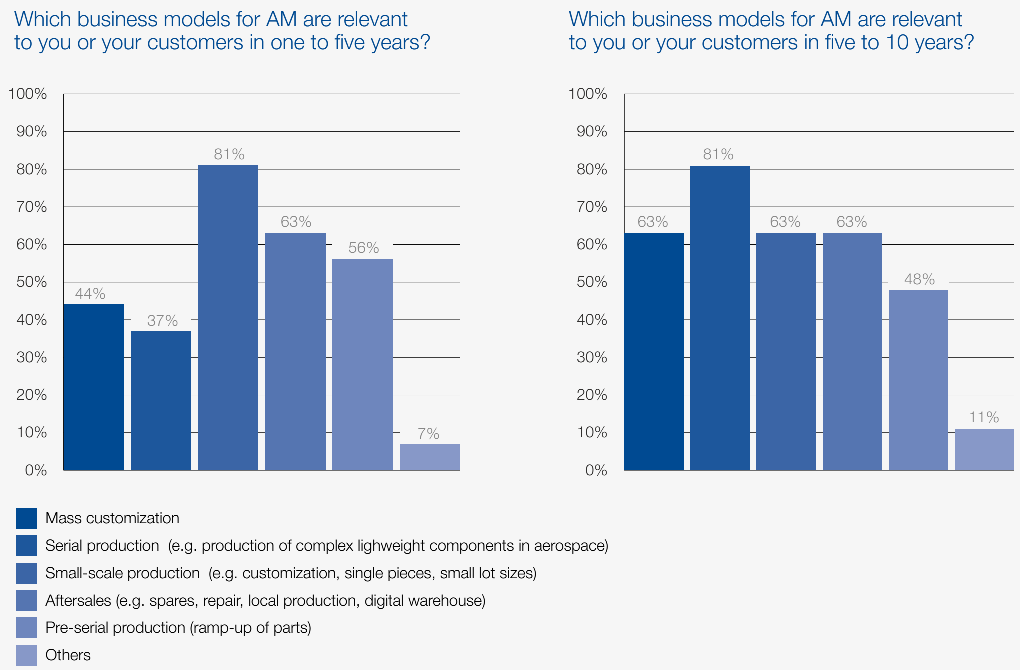
3.4 Strategize and support

Successful case studies such as the ones presented in this report underline the point that AM implementation typically needs to be of strategic importance within the adopting firm, since significant changes in the operational structure are often required. To address this, firms are encouraged to create an AM strategy very early on and align specific implementation projects with this roadmap. Furthermore, executives are typically required to provide top-level management support in the form of personal commitment and financial budgets for the implementation to succeed.

4 Future development and AM production scenarios

As a next step, the interview partners from industry and research were asked about their expectations through a standardized interview followed by an online survey on how AM opportunities will develop in the future and the affect on AM production (see Figure 4). The findings highlight a potential steady growth in the market over the next five years, fuelled by aspiring AM value creation and business models. For example, life-cycle support due to ramp-up and after-sales production, as well as small-scale production, seem to be feasible production scenarios. They could increase market volume and have the potential to bring the AM ecosystem towards industrialized serial production. In addition, market expansion through specialization in new niche applications could appear; for example, as a result of the development of new materials and technologies.

FIGURE 4 **Expert predictions on relevant AM production scenarios in the mid and long term**



Source: Fraunhofer surveys and interviews

To date, AM has been used for first small-scale production and to create significant revenues mainly by market and innovation leaders. This can be observed in markets such as consumer, aerospace and high-end automotive, as well as the medical and rail industries. Breakthrough market growth and acceleration will occur once (fast) followers start implementing AM. In the next five to 10 years, dissemination of knowledge could lead to a broader use of AM in the overall industry. Depending on advances within the AM ecosystem, production could shift towards fully integrated industrialization in all industry segments. Most experts do not expect disruptive developments in the near term, but rather foresee a slow and steady development; for instance, through continuous cost reductions. In particular, cost reductions could change the perspective on AM leading to a switch from strategic investment to a shorter-term ROI-based perspective – as seen in the case of well-established technologies. Consequently, a possible breakthrough for serial production and mass customization within five to 10 years is foreseeable. Life-cycle support such as AM ramp-up and after-sales production is estimated to be a relevant production scenario in the long term if the current roadblocks to AM are resolved.

In the long-term future, one potentially disruptive business model in the area of logistics and supply chains could be a digital inventory and warehouse, according to the experts surveyed. Product information (data) could be shipped from a digital warehouse instead of a physical one, potentially transforming supply chains by making them simpler, decarbonized and resilient. Many improvements have still to take place to enable new business models such as the digital warehouse.

5

Key enabler and solution approaches

On the basis of the interviews and identified challenges, the six most important enablers for the industrialization of AM have been ranked, in combination with solutions.

1. Reduction of manufacturing and process chain cost

   A significant increase in process speed in research and technical breakthrough techniques such as binder jetting have demonstrated great potential to reduce manufacturing costs in the next 10 years. Additionally, material costs are expected to further decrease due to new or improved material production methods and economies of scale. Automation along the process chain is under development and could lead to further cost savings, particularly in post-processing. As engineering experience grows, a better understanding of design-to-cost for AM is expected. In conclusion, it is possible that technical enhancements will lead to a leap in productivity and significant decrease in part cost compared to today.

2. Qualification of production and quality assurance

   It is possible to produce high-quality AM parts. But a less complex and costly qualification approach for additive manufacturing is needed to enable future production. For this purpose, the technical details of quality assurance, machine characteristics and AM material are clarified in joint coordination. Enhancement of quality-assurance methods such as in-process monitoring are a priority in current research. Overall, rather slow and continuous progress is expected in the development of simplified quality assurance and qualification.

3. Integration of AM and the digital process chain into production

   Only companies that are investing with a long-term strategic agenda and have consistent management support are today able to fully integrate AM as a production technology. The digital process chain – for instance, software for process planning – holds potential for a significant improvement. In the long term, in five to 10 years, Fraunhofer experts predict that AM could be an integrated production technology with a mature digital process chain.

4. Determination of further standards and norms

   Standards in AM are already progressing swiftly. Nevertheless, AM processes and operations, sustainability assessments, data formats and digital security need greater standardization. The widespread use of common standards is expected to increase the overall quality of AM and thus its level of acceptance, and the industrialization of AM across all industries.

5. Development of new applications

   The success of additive manufacturing market leaders is based on rethinking applications and processes using an intrapreneurial mindset. Identifying the right use case and the corresponding design is expected to be a key enabler in developing additive manufacturing business cases. A trend observed by Fraunhofer experts is the increased use of automated software in part design. Also, researchers are investigating new AM materials and combinations through multi-material solutions in order to multiply application areas. Ongoing innovations are expected to lead to new business cases, creating a further broadening of the market for niche applications.

6. Development of know-how

The dissemination and deepening of AM knowledge throughout the industry, including small and medium-sized enterprises (SMEs), can accelerate overall market growth. Surveyed experts predict an advance in this field in the next one to five years, but still rate it as a highly important enabler for the next 10 years. The slow progress of knowledge development in companies and the growth of new generations of students educated in AM require a long-lasting effort.

With the help of the six general enablers, specific requirements for AM future production scenarios can be derived. These are shown in Figure 5.

FIGURE 5

Requirements for AM future production scenarios

Future production scenario	Life-cycle support (ramp-up or after-sale)	Increased serial production	Digital inventory and localized production	Mass customization
Derived specific enabler	– Handover points between technologies when increasing or decreasing production volume – Common qualification procedure for AM technologies	– Decreased cost per part to gain competitiveness – Robustness of processes to minimize risks – Affordable quality assurance to reduce overall costs	– Common standards in AM to manufacture locally and on demand – Qualified materials to ensure safety requirements are met	– Automation of design to leverage individual solutions – Shared process data for an efficient digital backbone

Source: Fraunhofer surveys and interviews

6 Call to action

In order to accelerate the realization of the necessary enablers, this white paper concludes with a call to action for the global manufacturing community to carry the industrialization of AM a significant step forward. All stakeholders in the AM ecosystem need to **join forces** to overcome the issues created by AM's industrialization complexity and deliver AM's potential to the industry at large.

FIGURE 6

Seven steps to advance AM

- Reduce costs along the value chain through common investments
- Educate, share knowledge and designate "AM-intrapreneurs"
- Merge and push efforts in standardization
- Increase and streamline funding for TRL 3–6
- Enforce circularity and sustainability goals
- Raise quality awareness and simplify qualification
- Further the digitization of the process chain

Source: Fraunhofer surveys and interviews

1. Significantly reduce costs along the entire process chain through common investments

Technology suppliers and researchers are encouraged to push more in the direction of end users, who are placing focus on costs and the specific requirements arising from serial production. The development perspective must exceed the boundary of the AM system itself and include upstream and downstream processes. Funding and investments by collaborating partners along the process chain must be strengthened to decrease costs.

2. Invest in education, share knowledge and designate "AM-intrapreneurs"

First, existing efforts to educate engineers in universities need to continue and improve. Additionally, knowledge of AM needs to be passed on through commercial training programmes and knowledge transfer projects. Experts recommend that companies invest more in knowledge, skills and people than in machines. The current bottleneck is not necessarily due to a lack of machine technology, but rather a shortage of experts willing to promote AM technology and its benefits within the company. What could be called an "AM-intrapreneur" would be an evangelist for AM within a given company who has the exploitation of AM use cases within their annual targets. Governmental co-funding is an option to incentivize private personal and company training in AM. Knowledge development in the industry could be accelerated by dedicated transfer projects and using educational training programmes.

3. Merge and push efforts in standardization

Implementing standards across the industry, e.g. in SMEs, has to be a key goal. The standardization committees working in AM should keep on pushing forward and must be supported. Additionally, the benefits of using standards must be shown to companies in a broad and joint framework. Also, companies and academia need to put the standardization work back on the agenda of their employees. Governments should be willing to incentivize the participation of companies, research institutes and universities in the standardization process, to ensure state-of-the-art information through dedicated funding opportunities.

4. Increase and streamline funding to sustain research for technology readiness levels (TRL) 3–6

Together with universities, research institutions and public partners, organizations need to take steps to improve the landscape for AM-related technologies in TRL 3–6 in order to push those to industrial applications. AM is a complex technology that still needs intensive research, but declining AM research is to be expected if funding opportunities stay at the current level. Streamlining the process of governmental funding is an additional requirement, especially for software developments, cost reduction and quality assurance.

5. Enforce consequent circular economy and sustainability

Multiple experts reported that AM will benefit from a strong push in sustainability and can support, for example, carbon reduction. AM should be seen as a key part of the strategy enabling a sustainable transformation for governments and companies. Incentives such as funding or new regulations could drive the use of AM towards "cradle-to-cradle" (C2C)[12] and a circular economy. Additionally, several industry experts predict that taxing emissions could lead to further adoption of AM. Companies developing a comprehensive sustainability roadmap incorporating AM can create new assets for stakeholders and customers.

6. Raise awareness and investment for quality assurance and simplified qualification

Qualification could be a long-term drag on progress if no action is taken. Comprehensive research and a push towards less costly quality assurance must be undertaken. More and continuous investment into structured cooperation between part suppliers, end users, research, norming committees and regulation authorities could be a solution. For future industrialization, the qualification process must shift from an extensive part-by-part qualification approach to a general process qualification.

7. Scale digitization of the process chain

Digitization and consistent data availability along the whole process chain have to be improved, according to experts. Therefore, suitable data formats, standardized interfaces, opening of protocols and sharing of metadata should be enforced. Software and machine manufacturers need to collaborate and holistically improve the software process chain, especially when considering the evolving capabilities of AI.

By following the proposed call to action presented in this paper, a major leap in industrializing AM can be jointly developed from within the AM ecosystem. With these changes, the future business models and many new applications will be feasible in the next five to 10 years, leading to a steady growth of the overall market and offering disruptive potential for some industries.

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Endnotes

1. Eidgenössische Technische Hochschule Zürich.
2. Fraunhofer-Institut für Gießerei-, Composite- und Verarbeitungstechnik (IGCV); Fraunhofer-Institute für Produktionstechnologie (IPT); Fraunhofer-Einrichtung für Additive Produktionstechnologien (IAPT).
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12. This is the idea that resources can be used to make a product (cradle), then, at end of life, be reused to make another product (hence, cradle again).

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