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AM Automation

The road to a fully automated and digitalized additive manufacturing factory of the future

3dpbm

About
3dpbm is a leading AM industry media company. 3dpbm publishes 3D Printing Media Network, a global editorial website that has grown to become a trusted and influential resource for professional additive manufacturing.

Contact
info@3dpbm.com
www.3dpbm.com

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A Warm Welcome

This publication, our seventh AM Focus eBook edition, highlights a theme that reaches across the additive manufacturing industry and is at the core of the technology's industrialization. The topic I am referring to, of course, is Automation.

Automation is a necessary step in additive manufacturing's journey towards industrialization, and plays a significant role in all "Factory of the Future" visions. Automation is largely responsible for 3D printing's progression in recent years, enabling the technology to move beyond prototyping and become more viable as an end-use production and mass customization process. This eBook concretizes the concept of automation by looking at how it comes into play at each step of the AM process chain. From optimized design tools, to digital warehousing, to material handling, to printing, to post-processing and to workflow management, automation—through simulation tools, process management, AI-driven software and robotics—is what will move this industry ahead.

This eBook presents a comprehensive analysis of the market for automated AM factories (i.e. lights-out AM production or 3D printer farms), exclusive interviews with post-processing leader DyeMansion, automation-driven Ai Build, AM-Flow, Siemens and Schubert. The eBook also includes a roundup of the industry's Factory of the Future visions and more. The only way we could have fit more automation into this eBook is if a robot had written it!

Tess Boissonneault
Editor in Chief, 3dpbm

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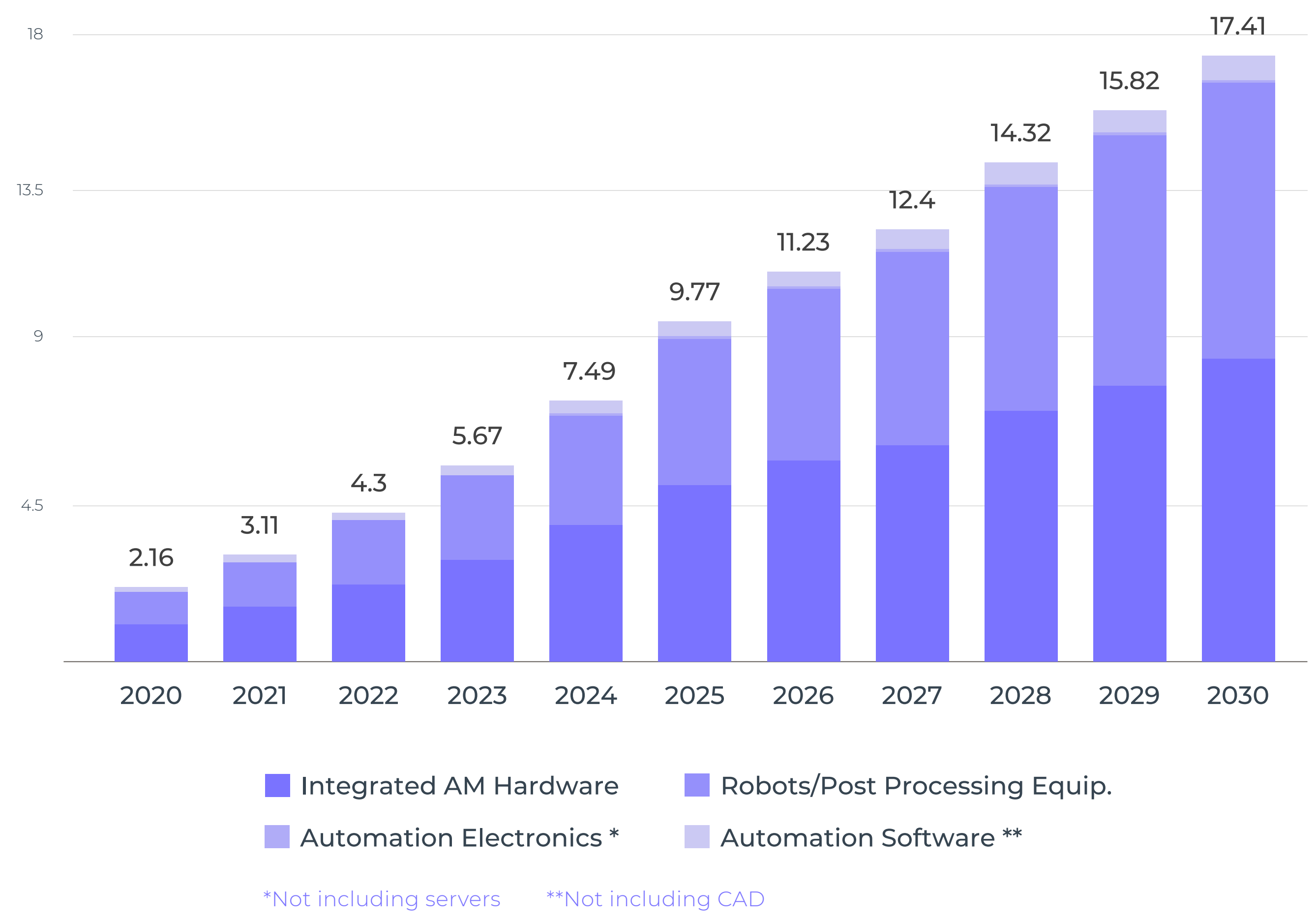
Take a look

Market for Automated AM Factories ($US B)

The overall market for automated AM factories will grow into a $15 billion revenue opportunity, with 23% CAGR driven by production, post-production and part/material handling hardware systems.

Source: 3dpbm



Analysis

The market for automated AM factories

3D printers were born as stand-alone prototyping systems—they are becoming swarms of automated production machines.

by **Davide Sher**

The trend toward fully automated factories is unstoppable and the recent COVID-19 crisis has only accelerated it. It's clear that the future of production will take place inside lights-off facilities that work around the clock, and if sustainability principles—as detailed in our dedicated Sustainability AM eBook back in May—are adequately implemented, the full automation of production will bring significant benefits to the global manufacturing industry overall, including both substantial productivity gains and the creation of new jobs.

While it is true that one of the ultimate goals in industrial automation is doing away with labor-intensive practices in massive centralized production centers, new jobs can also be created in terms of product design, system integration design and tailored, localized distributed manufacturing.

As major AM technologies increasingly offer (or at least promise) mass production solutions, AM adopters are fully realizing that 3D printing needs to be integrated into fully automated production lines in order to eliminate the bottlenecks that emerge in between different phases. These are both within the AM process and the overall end-to-end workflow automation, which includes file preparation, material handling, AM process, excess material removal and recycling, part removal, post-processing and part finishing.

In terms of automating the AM process itself, the biggest challenges lie in the ability to accurately evaluate a part's quality in-situ, leading to the decision-making process that follows in case of faulty parts. Data gathered throughout the process has to be evaluated in real-time to affect an 'on-the-fly' response in machining strategy.

In order to achieve a similar capability in AM systems, a new range of sensors (or repurposing of existing sensor technology), leveraging machine vision and AI capabilities along with new means of incorporating them into additive tools, is required. The temporal opportunity and the environment in which parts must be interrogated in-situ present significant challenges to researchers in this field. However, several researchers have tackled these challenges with some success and have produced demonstrable technologies, capable of acquiring useful data for informing process capability without the need for ex-situ analysis.

In terms of workflow automation, the primary challenges lie in the availability, programming and cost of robotic systems – including the 3D printers themselves—that are necessary for design, material, process and part handling. These are the—sometimes overlapping—four levels for automation in an AM factory or production plant. They are all part of the end-to-end digital AM workflow.

End-to-end AM workflow

Design automation

In order for all subsequent production processes to be automated, the digital end-to-end workflow has to start with automating the design process while taking into consideration AM's requirements. The very idea of DfAM began with the need to design a part so that it could fully leverage the benefits of AM in terms of part complexity. This is where topology optimization and CAE software tools evolved to help designers create better parts and products. It has now evolved beyond that.

DfAM now also needs to take into consideration the AM process itself, by enabling product designers to create parts that maximize AM productivity and reduce the need for post-processing. The next step, which is still largely unexplored, is the evolution of DfAM into a fully capable system of engineering tools, where AM parts can be designed to be part of complex systems, optimizing the size, weight, performance and efficiency of the entire system. The very idea of design automation also expands beyond DfAM, into the ideas of Digital Twin and Digital Warehouse, where the entire production workflow is digitized so that it occurs both virtually and physically, starting from either a new digital model or a replacement part model placed in digital storage.

Material supply automation

Only a few years ago, the idea of automating and centralizing material supply was just that, an idea. Today it's a reality in a growing number of both metal and polymer AM facilities. Material supply automation is easier

> "Only a few years ago, the idea of automating and centralizing material supply was just that, an idea. Today it's a reality."

to implement with powders. This is achieved through a central or local repository and overhead tubes that deliver materials directly to the machines. Efforts are underway to also automate polymer filament and pellet handling as well as liquid photopolymer resin supplies. Material handling also extends to material recycling. This takes place at the machine level and is more common for powder materials – both metal and plastic. Some options do exist for recycling unused and support materials for thermoplastics and photopolymer resins, however, automating these processes is more challenging.

Process automation

This segment includes the automation of all processes involved in 3D printing (the production process) itself. It is generally based on the specific machinery carrying out a particular task. Depending on specific approaches, process automation can also include automated post-processing and finishing stations (the post-production process). These processes are automated in that human contribution to the actual production, post-processing and finishing phase is limited to manually applying the desired settings. Full process automation is reliant on 3D vision systems and sensors as well as machine learning and AI to conduct in-situ process monitoring and make automated decisions based on part quality. Post-process automation relies on metrology and subtractive manufacturing software in order to accurately define and execute the post-processing requirements.

Parts handling automation

This part of the automation process covers all the systems and technologies required to move the parts from one station to the other, extract parts from a 3D printer's build platform. In some automated AM systems, support removal is also part of the part handling process. These robotic systems include both multi-axis robotic arms such as those used in several current industrial automation processes, as well as robotic cart systems that can carry parts from the 3D printers to the powder sieving, cleaning and post-processing stations.

Workflow management

Overall management of the end-to-end automated process is tied to MES (Manufacturing Execution Software). Depending on the available configurations – a large number of options exists today – this includes the software required to prepare a part for the 3D printing process, to analyze the part during the post process and, more generally, to handle and optimize all tasks using machine learning, data analysis and artificial intelligence software tools. Within the additive manufacturing factory of tomorrow, 3D printers take up a central role in a process that takes a product or part from early conceptual and CAD design to a finished product ready to be sold (in case of 3D printed consumer end-use products) or assembled into more complex structures (for industrial part manufacturing).

Full system integration and integrated system production are not yet considered within the digital AM workflow (although it should and will eventually be included). As AM becomes more of a batch-production capable technology, moving in-between stations has evolved from a task carried out by hand into one increasingly executed by robots.

Automating AM technologies

Each major 3D printing technology caters to specific industrial needs and has different automation requirements. The leading 3D printing system OEMs are approaching automation from different angles, with similarities and also significant differences between each technology's production cycle.

Material extrusion

There are two primary types of approaches to automating thermoplastic extrusion technologies. One is taking the thermoplastic extrusion process outside the confines of a cartesian 3D printing Architecture, by implementing multi-axis robotic systems. These robotic arms can operate more freely and multiple robots could even cooperate on producing the same part. Another is by using multi-axis robotic and even cobotic systems to place and remove parts from the printing chambers within farms with multiple, networked 3D printers.Automation in this segment also focuses on further automating the lengthy support removal and finishing process.

Polymer powder bed fusion

To date, the polymer PBF process is the most production-ready process available due to its ability to produce stacked parts using end-use thermoplastics. Now, with the emergence of high-speed planar technologies, such as Multi Jet Fusion from HP and High Speed Sintering from voxeljet, along with higher productivity from the latest SLS hardware, these technologies require a higher degree of process automation than ever before. Automation efforts in this segment focus on material handling (both supply and removal), part handling (cleaning and moving the parts) and part finishing (mainly smoothing and coloring).

Metal powder bed fusion

Metal PBF is the AM segment that has carried out the most research in process automation, industrialization and optimization.

It is also one of the most complex processes to automate due to the "standalone" nature of most current metal PBF systems and the critical nature of the parts generally being manufactured using this technology, which often present very high requirements in terms of both process repeatability and part validation. Automation in this segment focuses on part and process simulation, process monitoring and process management, as well as powder (supply and removal) and part handling (finishing), with a very high emphasis on software.

Metal deposition

Metal Deposition (DED) is the most automated of all AM processes as it is derived directly from the experience of the machine tool industry—which is among the most automated industrial segments. Players in this segment view the "AM Engine" as an additional tool that can be integrated into the set of tools already used in advanced machine tool systems. These already include metrology and CNC (subtractive) capabilities that are necessary for end-to-end part production.

Photopolymerization

Automation in photopolymerization processes is, interestingly, a combination of practices adopted in PBF and extrusion processes. Some approaches include the use of a multi-axis robotic arm to handle parts in multiple production stations or production cells. Other approaches focus primarily on automating the post-processing and curing phases. Much like PBF processes, these technologies are now demanding a higher degree of process automation as they are now able to implement end-use materials at much higher production rates.

Binder jetting

Binder jetting technologies, which selectively deposit binder onto a bed of powder, were at one point considered the most labor intensive and the least likely to offer ideal solutions for production. However, they are now emerging as some of the most production-friendly systems due to lower costs, higher speeds and the ability to produce parts of almost any geometry without supports.

Metal binder jetting post-processes such as debinding (to remove binder), infiltration (to reduce porosity) and firing of the green parts (in a furnace) are proving to be easier to automate than some of the tasks required in metal powder bed fusion (such as support removal in geometrically complex parts).

The market for automating AM

In light of the significant advancements in the automation of additive manufacturing that have taken place over the past two years, the market for automated AM factories is now expected to generate $15 billion in yearly global turnover by 2030. This would indicate 23% CAGR, from the current level of ~$2 billion.

The term *AM Factory* here represents any facility with at least 10 production-ready, metal and/or non-metal (polymers, composites and ceramics) AM systems, which are networked and connected with a high level of automated material/part handling and post-processing.

The revenue figure considered here includes four major segments—each divided between metal and non-metal AM production. These are AM Hardware, Robots and Post Processing Equipment, Electronic Components (excluding servers) and Automation Software (excluding CAD).

The opportunity for electronics in automating the AM factory is a very marginal one in terms of revenues, due to the relatively low number of AM factories. In spite of high overall market value, AM is still expected to continue to represent only a very small percentage of manufacturing throughout the forecast period outline here.

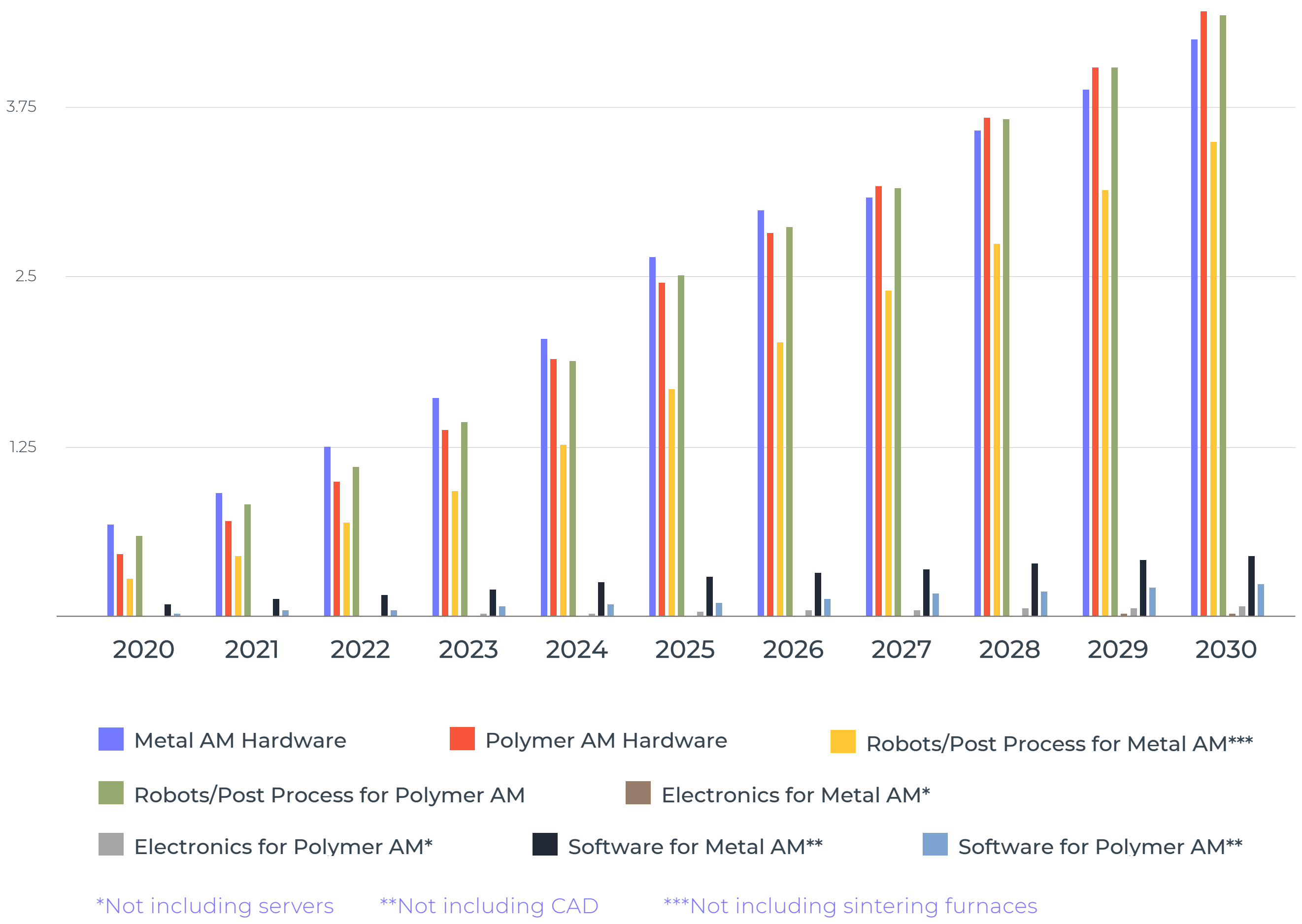
This analysis, however, also indicates that the cost of establishing the electronics infrastructure in the AM factory will be very low when compared to system costs, further incentivizing the adoption of connected and automated manufacturing processes.

Finally, software will play a key role in driving automation for AM. This report specifically takes into consideration the software that is very closely linked to automating the mechanical aspects of the AM production cycle, including process and workflow automation, and thus excludes most pre-production tools (CAD, CAE, CAM) and post-production tools (ERP, CRM). Automation across all of these software stages is, however, vital. ◆

Market for Automated AM Factories by Polymer/Metal Subsegments($US B)

The key driving segments in the automated AM factory market are powder systems for production, both metal and non-metal. Post-production and part material/handling are the next most important subsegment, however, the lower productivity of most current metal AM systems (including faster DED and binder jetting) indicates a smaller opportunity for metal post-processing equipment than is the case for plastics..

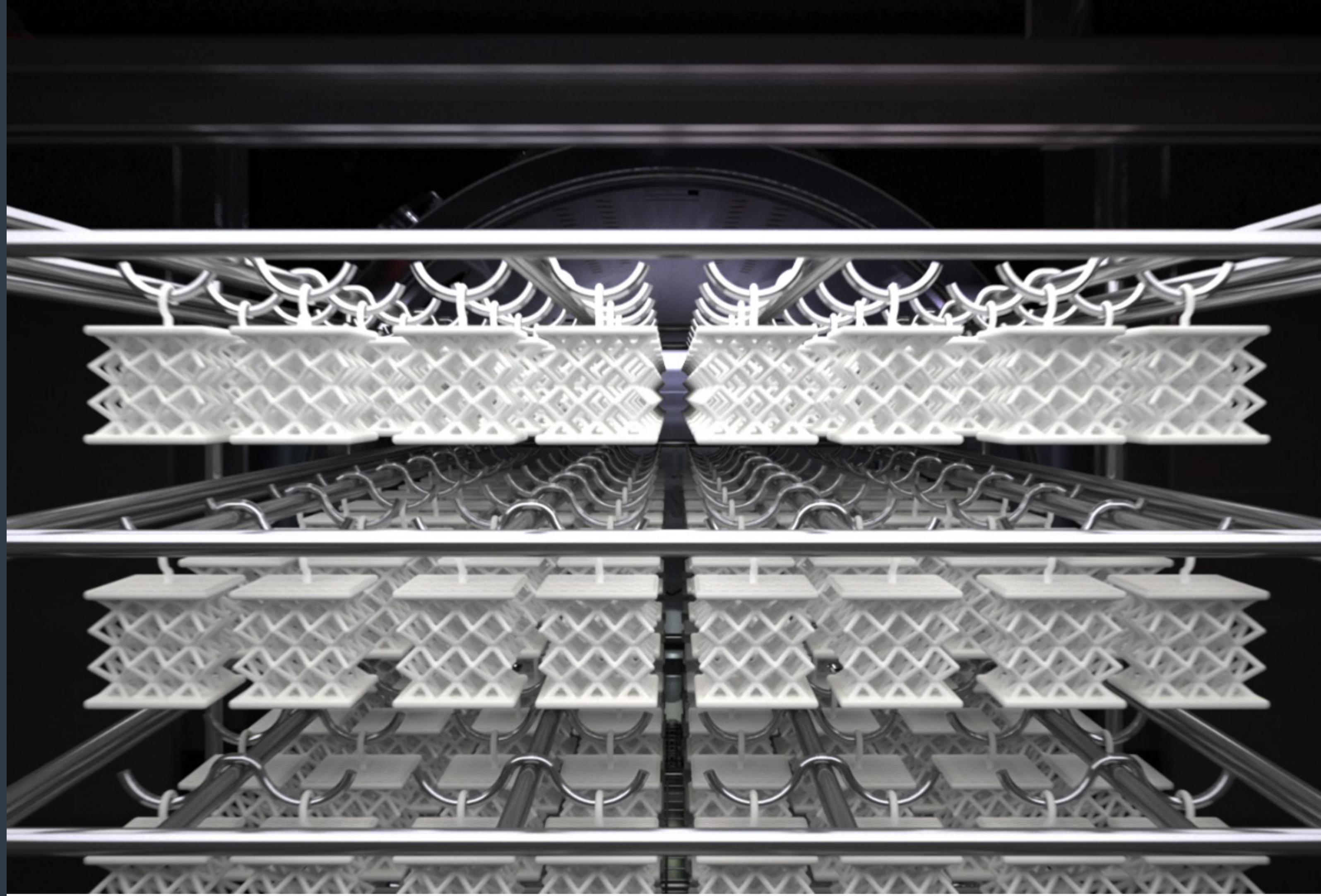
Source: 3dpbm



Interview

Entering a new DyeMansion

Since introducing their first solution for SLS coloring in 2015, DyeMansion has become the reference for industrial post-processing. We sat down with the founders to learn more about their vision and technology.



Serial parts undergoing vapor treatment in the Powerfuse S: as polymer chains rearrange surfaces become smooth and completely water tight.[1]

Quoting a popular fictional character, post-processing can be described as "The cause of—and solution to—all of 3D printing's production challenges".

It is the cause of said challenges because 3D printed parts require intensive post-processing steps, more so than any other manufacturing technology. It is the solution because the only way to achieve fully digital manufacturing workflows is by solving the additive post-processing challenge.

Only a few companies in the world of AM have made this their priority and no company has achieved as much success as DyeMansion has in just five years on the market. DyeMansion went from seed funding—supported by AM Ventures—to establishing a strong presence in Europe, with increasingly consolidated distribution in both the US and China, to a €5 million Series A funding round led by financial investors Unternehmertum Venture Capital Partners (UVC Partners) and btov Partners.

"As of July 2020, we have 18 sales partners around the world to cover market demands locally," Co-founder and CEO Felix Ewald tells us. "We strongly believe that you have to do local business with local people. We have known from the very beginning that we need to become a company that acts globally. Even the first four machines that we ever shipped were installed in four different countries. Internationalization has never been a question mark for us and today we have over 700 customers using our hardware or On-Demand Finishing offer from 34 different countries. Since our Series A funding in 2018, we doubled our team and are now 66 FTE in our two locations in Munich, Germany, and Austin, Texas. That makes us proud!"

DyeMansion's expertise has grown so much that it was selected to be part of the €10.7 million POLYLINE project, together with 15 industrial and research partners alongside EOS and BMW. This collaboration is one of the drivers to accelerate automation and integration into MES systems and its goal is a fully connected production line at BMW's new Additive Manufacturing Campus. "This is proof that we are already on the right track," says Co-founder and CTO Philipp Kramer. "DyeMansion takes care of the post-processing to complement the line beside areas like software and printing."

The road ahead is still a very long one and the company's co-founders have a very clear idea of where they—and

DyeMansion co-founders Philipp Kramer (left) and Felix Ewald (right).[2]

"The demand for post-processing depends heavily on the adoption rate of 3D printing by the manufacturing industry."

by extension, the entire polymer additive manufacturing industry—is heading. In this exclusive interview, we speak about their strategy to continue on their (and AM's) exponential growth path and the technology that will make it happen.

3pdbm: *What is your long-term vision for fully automated post-processing?*

Felix Ewald: I don't have a vision just for post-processing. My vision is much bigger: that true, digital manufacturing becomes a reality and 3D printed products become part of our everyday lives. In my opinion, this is key to a sustainable economy. Of course, post-processing is an important element of that and we will do our best to accelerate the transformation of the manufacturing industry. We will focus on unlocking all imaginable end-use applications of 3D printing by delivering best-in-class technologies that fulfil all industry 4.0 requirements and fit perfectly in the factories of the future.

3pdbm: *Let's take a step back, why did you start with dyeing?*

FE: Our first business idea regarding 3D printing was selling customized smartphone cases. The biggest challenge that we faced was that the color did not last. That's why we started developing our own dyeing solution. Once we recognized that this was not only our issue but also a big challenge for the whole industry, we switched our focus from smartphone cases to professional post-processing equipment. It was clear from the start that coloring always comes up with some kind of surface treatment. But of course, we could not have imagined that the demand for post-processing solutions goes for almost all applications and industrial printing technologies out there.

3pdbm: *Fast forward to now, can you talk a little more about the latest addition to your Print-to-Product workflow, the Powerfuse S?*

Philipp Kramer: The Powerfuse S uses the VaporFuse Surfacing (VFS) technology and complements our existing portfolio of surfacing techniques. Our customers already made many applications become reality with our PolyShot Surfacing (PSS), introduced in 2016, which delivers a high-end semi-gloss finish through mechanical blasting. Still, there was an untapped potential of applications in need of truly sealed and washable surfaces, especially when using flexible materials like TPU. For both, chemical surfacing with a solvent vapor is the only suitable solution. This is exactly what the Powerfuse S does.

DyeMansion identified key features that will be needed for the equipment of the digital factory of the future and implemented them into the Powerfuse S.

An example of Print-to-Product workflow at Daimler Buses: the part was first cleaned in the Powershot C, then treated with PolyShot Surfacing (PPS) on the Powershot S. Finally DeepDye Coloring (DDC) was applied in the DM60.[3]

The solvent in the Powerfuse S is circulated continuously in a closed loop and automatically recovered by the system which allows for a sustainable contact-free process without chemical waste.[4]

3pdbm: *Can you explain how the technology behind it works?*

PK: Basically, solvent vapor condenses on the surface of the parts. This dissolves the top layer of the surface causing the polymer chains to rearrange in the strive for low surface energy. The surface roughness is heavily reduced and after removing the solvent from the part, there is a smooth and completely sealed surface. For a long time, chemical smoothing has been associated with harsh chemicals, toxic waste and single-use solvents. This not only can cause serious harm to the operator, sometimes even using CMR-solvents (carcinogenic, mutagenic and reprotoxic), but also has a bad environmental footprint. Additive manufacturing has huge potential for a more sustainable supply chain and all post-processing steps need to support this vision. For us, it was a prerequisite solving all those challenges, before offering a system to the market. The Powerfuse S runs with a solvent that is approved by the EU for food packaging and is used in many cosmetic products. It operates in a fully closed loop with integrated recycling of the solvent and no waste. We managed to develop a truly green solution here.

3pdbm: *How does it integrate within Industry 4.0 workflow automation?*

PK: Industry 4.0 is quite a broad term that is often just used as a buzzword. With the help and knowledge of our industrial customers and partners, we identified key features that will be needed for the equipment of the digital factory of the future and implemented them into the Powerfuse S.

In concrete terms this means full process monitoring using sensors, connectivity features with the modern OPC-UA protocol for machine-to-machine communication and integration with MES/ERP systems, as well as remote maintenance via a VPN for fast solution finding in case of a failure to ensure a high OEE (Overall Equipment Effectiveness).

On the automation side, a conveyor belt proved to be the most efficient and flexible solution to enable autonomous runs in the absence of an operator. In addition, the conveyor belt gives the flexibility to either move treated parts to the next processing step via a conveyor extension or load and unload the system using AGVs (Automated Guided Vehicles).

3pdbm: *What are some of the biggest challenges of post-process automation?*

FE: Managing the complexity of serving different materials and printing technologies. Every printing technology and even almost every material behaves differently in terms of coloring and surface treatment. We are aiming to help our customers with all their challenges.

But if you just consider 10 materials from 10 different suppliers, you already need 100 adapted processes which makes it quite complicated and also hard to prioritize. The good thing is that we learn with every new material and new customers can benefit from this know-how and our database.

3pdbm: *Can you explain which software is necessary to run and integrate your systems?*

PK: In general, the Powerfuse S is a stand-alone system that does not require any centralized software to run. On the integration and industrial automation, we decided to use the newest Siemens components that support the modern OPC-UA communication protocol. This currently emerges as the industrial standard for machine-to-machine communication. The leading MES software providers are working on an integration via the OPC-UA protocol or are already supporting it as of today. With the rise of the importance of post-processing, we have been contacted by the most relevant players in this field and are currently speaking about an out-of-the-box integration of the Powerfuse S and other DyeMansion systems within their software. The need is definitely there and it offers a high customer benefit.

3D printed earrings by BOLTENSTERN, produced with EOS SLS technology and finished using DyeMansion's Print-to-Product Workflow.[5]

> **“Managing the complexity of serving different materials and printing technologies is one of the biggest challenges.”**

3pdbm: *Will more DyeMansion systems adopt a conveyor belt for workflow integration in the future?*

PK: With the great feedback that we received from the concept of the Powerfuse S with its conveyor belt and the connectivity for communication, it is a logical step for us to develop such solutions for the complete DyeMansion workflow. The automation of the individual systems is not the biggest challenge. The interfaces between different systems, both in data flow and part flow, is the greater challenge. Most likely this will require the most work and creativity as well as expertise.

3pdbm: *Could robots also be used to move the parts from one station to the other or will conveyor belts be the standard means of connecting all stations?*

PK: I do not think there is a perfect solution that fits all needs when it comes to automation. Customer production environments and requirements are highly individual and you cannot compare one with the other in most cases. Producing slightly individualized parts with similar geometries at high volume, as is the case with eyewear, for example, requires a different concept than having build jobs with thousands of different parts in different sizes, from different customers. Key is to have flexible systems that can be integrated into any manufacturing environment. Then it doesn't matter if the customer wants to use robotic arms, conveyor belts or AGVs. The post-processing equipment must be able to serve all those cases.

3pdbm: *How large of a demand for post-processing hardware do you expect over the next 5 to 10 years?*

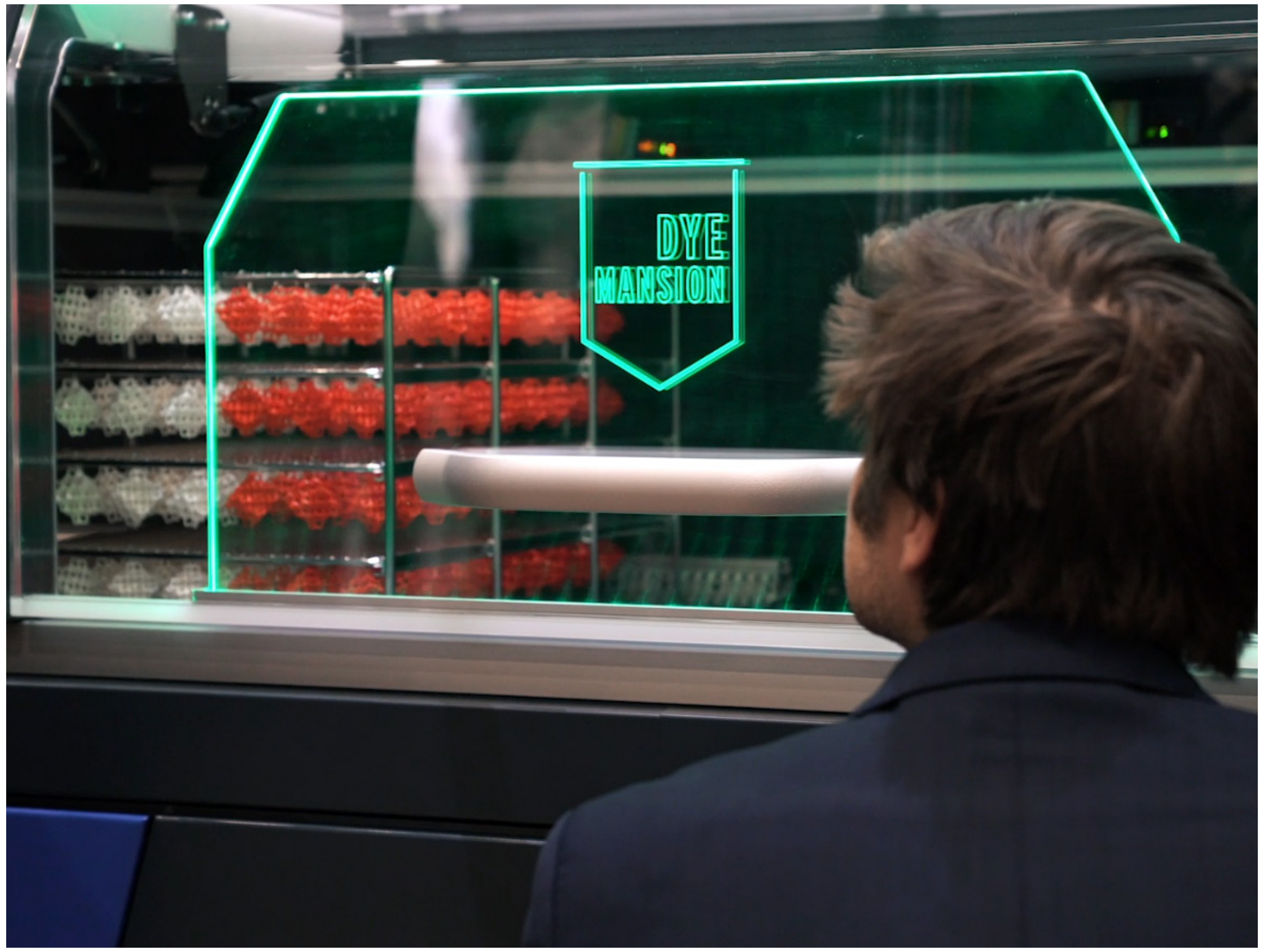
FE: The demand for post-processing depends heavily on the adoption rate of 3D printing by the manufacturing industry. If you don't have an industrial 3D printer, you don't need our solutions. So everything is connected. The CAGR of AM is expected to be around 25% for many, many years to come. Another accelerator is the switch from prototyping to real manufacturing.

The demand for automated and high-quality finishing solutions increases having larger manufacturing applications at scale. So, on the one hand, we depend on the general development of 3D printing. On the other hand, we accelerate development because our solutions unlock the full potential of 3D printing by enabling the production of high-quality finished parts.

3pdbm: *Is the current workflow based on 3 types of hardware (cleaning, smoothing, dyeing) complete or could more systems and stations be integrated in the future?*

PK: The current workflow will be extended by further solutions in the future. There are some challenges that have not been solved yet. For example unpacking of the build cake, part handling/sorting and quality control. We at DyeMansion will cover the entire process chain after the successful build of the parts when they leave the 3D printer. Those extensions will be fully integrated into the existing workflow, which makes our equipment a safe investment for the future. Whether we develop our own solutions or work with partners will be decided on a case-by-case basis. Forming strong alliances with specialized category leaders will be the key to meet all post-processing requirements.

The Powerfuse S is Industry 4.0 ready with an automatic loading and batch-tracking features.[6]



The Powerfuse S uses Siemens automation technology and is integrated in their digital AM factory planning tool.[7]

3pdbm: *Will DyeMansion consider introducing other types of hardware for AM workflow automation, such as metrology, NDT, even pre-process hardware for material supply?*

PK: Keeping the focus as a start-up on the key areas of expertise is quite important. In the field of metrology and NDT there are several companies that are specialized in those technologies. Most likely such solutions will be integrated into the post-processing chain. Pre-processes like material supply and storage have a high influence on the print itself and the quality of the parts. Printer manufacturers have the most expertise here and it should be handled by them. Most suppliers already have equipment in their portfolio. So, there is no value for the customer if we create our own solutions.

3pdbm: *Will you ever get into metal post-processing?*

FE: Never say never, but so far we have no concrete plans to go into this direction. Our goal is to be the best in what we do. Metal post-processing is a completely different field that requires completely different solutions. We have so many products and topics in our pipeline that will keep us busy for the coming years and define our roadmap. ◆

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Interview

Time for AM factories to get in AiSync

Ai Build set out on a quest to automate large-scale robotic 3D printing. This is how they did it and with AiSync, you now can too.

Ai Build's autonomous additive-subtractive robots manufacturing a jig for a Formula E race car.[8]

On the topic of AM automation, London-based Ai Build needs no introduction. The company, which has brought to market a large-scale robotic 3D printing platform, was founded with the express goal of solving automation-related challenges associated with additive manufacturing.

Many across AM will be familiar with Ai Build for impressive collaborations within the architecture and design worlds—including an amazing 57-square-meter pavilion at the Venice Biennale in 2018—but Ai Build is a technology company at its core, one with goals to continually advance and adapt to the market and its needs. In the following interview with Ai Build Co-Founder Daghan Cam, we learn about the company's automation mission with an increasing focus on industrial sectors like aerospace and automotive, as well as its AiSync software that automates large-scale additive manufacturing.

Ai Building something new

Ai Build was founded in 2015 by Daghan Cam and Michail Desyllas, two innovative minds with backgrounds in architecture.

"We could see a big potential for additive manufacturing in various industrial applications," Cam tells us. "But at the same time, we were frustrated with the fact that the technology didn't scale up well for the

“AiSync uses analysis and simulation tools with high computing power on the cloud to determine the optimal toolpath for a given project within seconds”

applications we wanted, like architecture and construction. Every minor problem in traditional desktop size 3D printing is multiplied in large-format AM by a factor of 10 or more, making the entire process from design to finished part extremely hard. That’s why not many people have even considered 3D printing at such large scales until recently.

“Our starting point was to investigate what makes AM, particularly in large format, so inaccessible. It didn’t take long to understand that the lack of automation was the biggest barrier, by far. We were seeing days or even weeks of manual toolpath engineering attempts for fabricability of parts and failure rates were about 40 to 60 percent, which was totally unacceptable. We broke down the process to understand where exactly the lack of automation was coming from. We looked at what happens before printing begins: how users are optimizing their designs, how process parameters are selected and how designs are processed through slicing software. At the time, these steps were very much based on the process knowledge of machine operators combined with lots of trial and error. We thought there could be a better way to do it, an automated way to achieve consistent results with additive.” That, Cam says, is how he and Desyllas came up with the AiSync platform for autonomous large scale 3D printing.

Ai Build’s solution

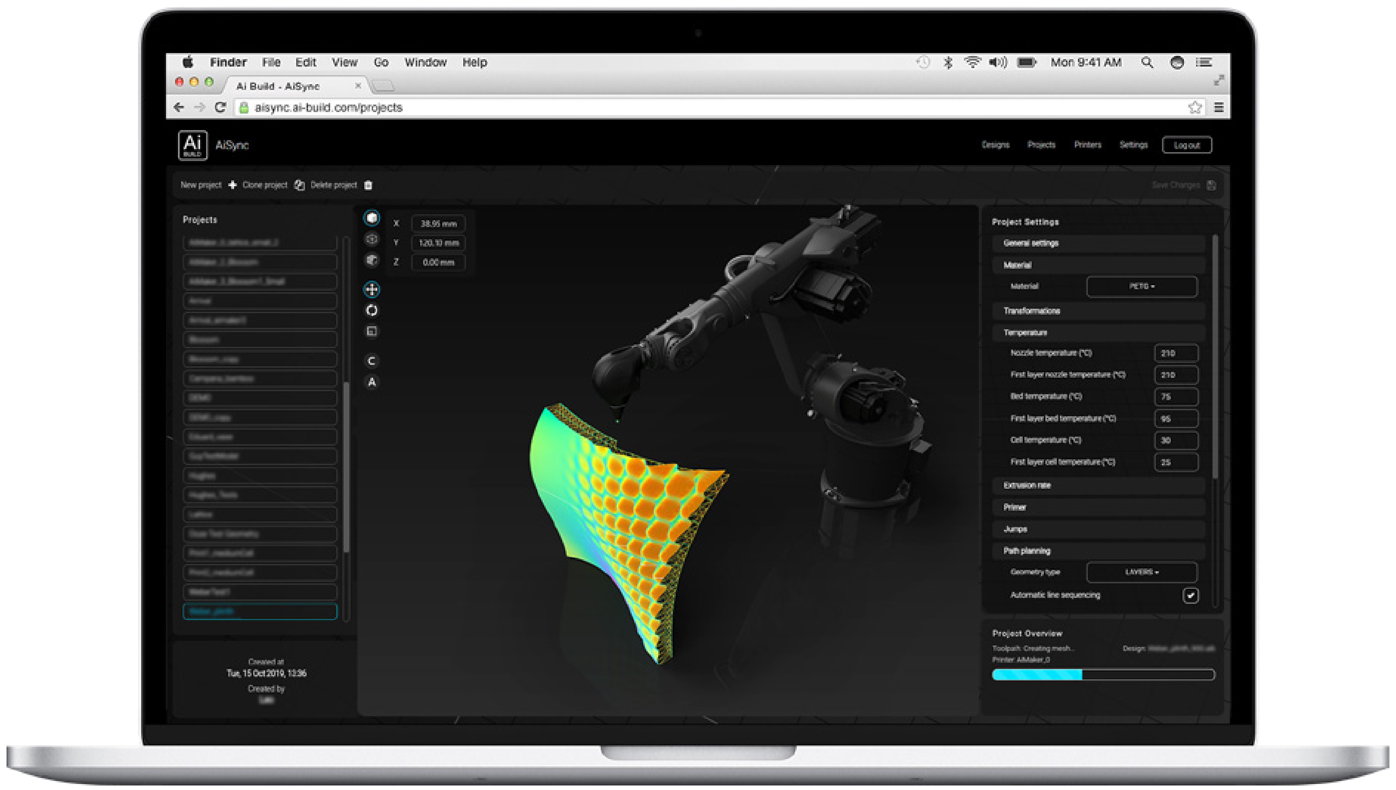
Ai Build’s solution to large-scale additive manufacturing consists of a few components: the AiSync software, an FFF/FGF based polymer extrusion system, an optional enclosure for environmental control and a robotic arm. This multi-component configuration allows the company to develop large-scale 3D printing features for a wide range of hardware solutions. At the core of Ai Build’s recommended hardware setup is an industrial robotic arm from KUKA, a manufacturer of industrial robots and solutions for factory automation, with UK headquarters in Wednesbury, West Midlands.

Cam explains: “We needed a very robust actuator that should be fully reliable and never fail. In order to achieve that 100% guarantee of success with the hardware, we partnered with KUKA, as official system partners, who are very well known for high precision and highly reliable industrial robotic arms.”

The second key component on the hardware side is the AiMaker, the company’s own extrusion system, capable of extruding thermoplastics and composites at a rapid rate of 3 kg per hour. “Developing an autonomous 3D printing technology is like developing an autonomous car. You cannot build a self-driving software and install it on any car in your backyard. The hardware needs to support the software with specific performance, sensors, cameras and computers.”

Cam says of choosing to develop a new extrusion system for large-format AM: “The existing extruders on the desktop 3D printing market were too slow, too unreliable, and they didn’t have the electronic components required for real-time control. So we built the AiMaker from scratch, which is to date the world’s fastest FFF extruder on the market. Luckily, this gap for commercially available hardware components for large format AM has been filled in the last couple of years. Several European and American OEMs have released powerful large-scale 3D printers and today there is a healthy number of hardware options to choose from in this new and fast-growing AM category.”

AiSync allows the users to upload CAD designs and automatically generate optimized toolpaths for large scale additive manufacturing.[9]



Ai Build's vision for the factory of the future: Autonomous, cloud-connected and primarily additive.[10]

All hardware components that are compatible with Ai Build's autonomous large-scale 3D printing technology, are equipped with an array of sensors, cameras and computers which communicate with the AiSync software.

AiSync: the key to the puzzle

AiSync, in the simplest terms, is a cloud-based software that takes design files and generates optimized machine instructions for large-scale 3D printing automatically. The software makes additive manufacturing of large components such as molds, jigs, fixtures and end-use parts as easy as clicking a few buttons on a web platform.

"The first thing that sets AiSync apart from conventional 3D printing software packages is that it takes full advantage of the additional degrees of freedom that come with the robotic arms," Cam says.

"3D printing typically works in a linear layer-by-layer fashion, so by moving the extruder in three dimensional space without constraining ourselves to flat layers, we can produce very efficient structures in much shorter timeframes and in higher quality. AiSync's multi-axis motion planning features allow our users to achieve structurally optimized 3D infills, non-planar slicing and even non-planar hybrid additive-subtractive treatment of surfaces with minimal effort.

"With additional degrees of freedom, however, comes the challenge of toolpath design and optimization, because there are almost infinite ways to create a path in three-dimensional search space. AiSync uses analysis and simulation tools with high computing power on the cloud to determine the optimal toolpath for a given project within seconds, eliminating the need for excessive human labor and time-consuming trial and error."

In addition to automating this part of the additive manufacturing preparation, AiSync also plays an important role during the printing process. "The second aspect of the software that increases the level of automation dramatically is real-time communication with robots," Cam continues. "Most 3D printers on the market take a G-code file and blindly execute it without having any control over that process, which is the exact opposite of autonomous manufacturing. Essentially, if anything unexpected happens, the process will fail, which is highly likely in large-scale AM. For this reason, we abandoned G-code and developed a completely new machine control process from scratch that is resilient to environmental, material and hardware related inconsistencies." The robots driven by AiSync exchange data with a computer bi-directionally in real-time. Ai Build refers to this edge device as the AiSync Printer-Server which gives the ability to detect and compensate for common problems on the fly, with significant savings on time and materials.

"As a result of AiSync's powerful simulation and optimization capabilities, our users achieve high quality production parts in short amounts of time without even noticing the difficulties associated with large-scale additive manufacturing."

Opening up the technology

One of Ai Build's latest (and very exciting) announcements is that it is working to open up its technology to other manufacturing companies. Cam says: "Initially AiSync was developed for the AiMaker, but more recently, we started integrating it with other industrial 3D printers. We have already partnered with several hardware manufacturers and that is keeping us very busy these days." At the moment, these integrations will be focused on other large-scale multi-axis 3D printers, though Cam says most of its processes can also be used for gantry 3D printing systems.

"We have announced our first partnership on AiSync with Weber Additive, a German manufacturer of industrial 3D printers with more than 100 years of experience in machine development and manufacturing" Cam reveals. "By combining the advanced control and monitoring features of AiSync with powerful industrial machines built by Weber, we are bringing to market highly automated and robust large-scale additive manufacturing solutions for heavy industrial applications."

Cam exclusively anticipates that the company will soon be unveiling the first AiSync powered Weber machine—a multi-axis large-scale 3D printer including a Kuka robot and a Weber AE020 pellet extrusion system. "This partnership allows us to scale our operations in key industrial markets such as automotive and aerospace," he says.

AiSync provides insights and a comprehensive overview about production quality and performance with its real-time monitoring tools and analytics dashboard.[11]

Envisioning the future

Down the line, Cam has a clear vision for how the Factory of the Future could play out, one in which automation drives lights-out production and additive is the key manufacturing process. “The advantages of additive are quite obvious to us: it’s the most material efficient way to do things, and it’s also very capital efficient: you don’t need expensive tooling,” he states.

“What became very clear with COVID-19 is that AM is also the most efficient technology for the supply chain,” he continues. “It eliminates transportation and storage because everything is done on demand. The biggest obstacle holding back the technology right now is the lack of automation. At Ai Build we are constantly asking ourselves what needs to change to achieve higher levels of automation and we are working closely with our industrial partners to accelerate our move towards autonomous lights-out manufacturing.

“One key technology that needs to be embraced by manufacturers to increase automation is cloud connectivity. Before COVID-19, highly regulated industries like aerospace were concerned about storing their data on the cloud, but now that is loosening up a bit with the increasing desire for automation. Cloud, when done correctly, can be more secure than on-premise solutions. This is already proven in other services like CRM platforms and accounting software that became almost entirely cloud-based in the last few years. Our mission at Ai Build is to enable the factories of the future that are autonomous, cloud-connected and primarily additive. There is of course a lot to do, but we are moving rapidly in that direction.” ◆

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Mapping

Today's automated AM factories

How leading companies across the additive sphere envision the Factory of the Future.

Siemens' vision for the AM factory of the future encompasses the concepts brought forth by several partnering hardware manufacturers, including EOS.[12]

Several large 3D printer manufacturers have announced and displayed their vision for automating production in an additive manufacturing-based factory.

These include key additive manufacturing hardware OEMs as well as large machine tool manufacturers, which can leverage extensive experience in factory automation, adding the "AM engine" as an additional tool for directed energy deposition within hybrid manufacturing. The integration of powder bed fusion (PBF) technologies within the automated factory presents a greater order of magnitude in terms of additional complexity, as it is, by definition, confined to an enclosed powder bed.

Siemens

As the leading provider of design, process optimization and PLM software, Siemens' vision for the AM factory of the future encompasses and enables the concepts brought forth by several partnering hardware manufacturers, including EOS (for metal and polymer PBF), Stratasys (for polymer and composite material extrusion), HP (for polymer MJF) and ExOne (for metal binder jetting), among others.

This vision centers around the NX software capabilities and expands to include Siemens digital warehouse and digital twin concepts. Siemens has already implemented this

GE's Additive Technology Center in Cincinnati, Ohio has nearly 90 3D printers in operation, including six large-scale X Line 200R systems.[13]

automated AM factory vision in several internal production facilities, notably the Siemens Materials Solutions facility in the United Kingdom.

GE Additive's Factory of the Future

The GE vision for the automated AM factory is very much based on Concept Laser's vision. Acquired by GE in 2016, Concept Laser was among the very first industrial 3D printer OEMs to devise a vision for automating 3D printing. The M LINE FACTORY forms the core element of the "AM Factory of Tomorrow," which also envisages linking up with traditional manufacturing methods in the post-processing of parts. The concept consistently implements the basic idea of "Industry 4.0" with a focus on delivering a "smart factory." Consistent automation, interlinking and digitization of all processes ultimately allow the economical series production of additively manufactured metal parts.

The new machine architecture is essentially characterized by decoupling "pre-production," "production" and "post-production." This includes, among other things, flexible machine loading and physical separation of the setting-up and disarming processes. This becomes possible thanks to a consistent modular structure of handling stations and build and process units that, in terms of combination and interlinking, promises considerably greater flexibility and availability. It will also be possible to handle the present diversity of materials better and more economically through a targeted combination of these modules.

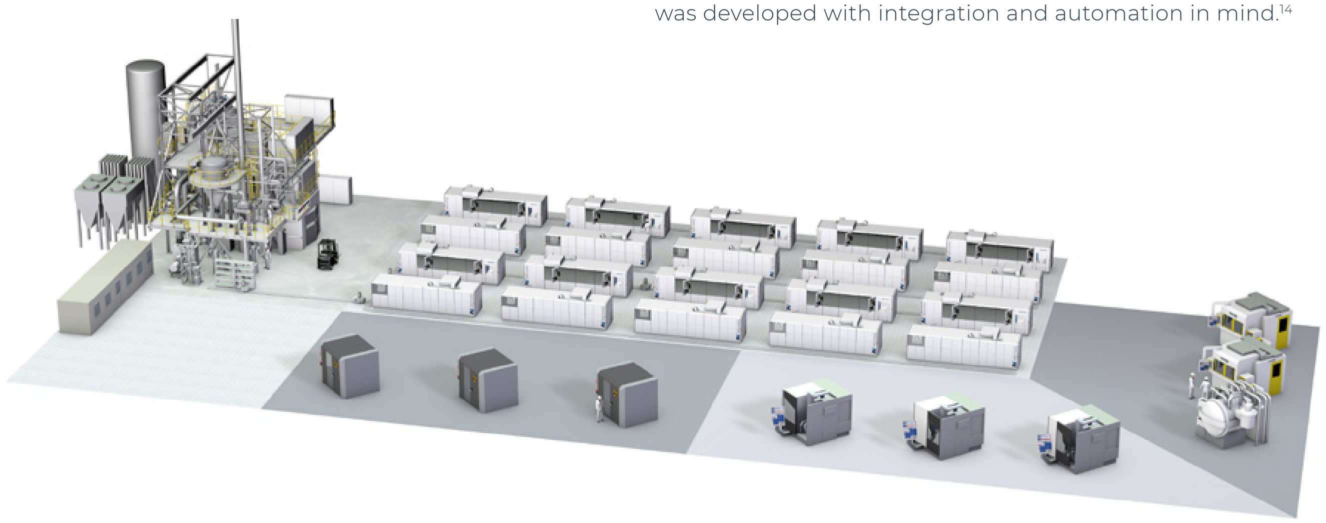
The new approach also envisages dividing the material storage facility, the processing unit and the unit for collecting excess material into individual modules. These modules are independent of one another and can be controlled individually. Simulated production scenarios have in fact shown that this space can be reduced by up to 85% compared to the possibilities that exist at present. In addition, the laser power per square meter of area used is increased seven-fold.

Additive Industries and SMS Group

Additive Industries MetalFAB1 system is the first platform built and commercialized specifically with automation in mind. It is an integrated machine that includes printing and post-processing, with automated handling of build plates and powder materials. This allows for 72 hours of continuous operation without human intervention. To help this manufacturing process break through into serial production, Additive Industries and SMS group have agreed to develop and jointly market a production system for additive manufacturing on an industrial scale. The production concept will not just encompass powder manufacturing and 3D printing but other stages, too, right up to the delivery of the finished component.

In this vision, the process starting point is the production of powder. To ensure maximum purity, the alloys are induction-melted under vacuum in the crucible. The liquid metal is atomized using pure argon in an oxygen-free atmosphere. The powder manufacturing process is followed directly by 3D printing in the integrated MetalFAB1 system. After additively manufacturing the parts, the build plate with parts is automatically transported by a robot to the heat treatment furnace

From the beginning, Additive Industries' MetalFAB1 system was developed with integration and automation in mind.[14]



for a stress relief cycle before storage. The MetalFAB1 system is designed to run autonomously without the need for multiple shifts, substantially reducing cost. SMS group is also responsible for the heat treatment of the printed components and for the setting of improved material characteristics. Within the group, SMS Elotherm is the company with the induction heat treatment expertise.

EOS NextGenAM

EOS worked together with automotive manufacturer Daimler and aerospace tier-1 supplier Premium Aerotech on the NextGenAM project for AM implementation in large-scale serial manufacturing.

The objective of the project is to advance the automation of the entire industrial AM process. The NextGenAM additive production chain is highly scalable and is fully automated. No manual work is required at any stage of the process, from the print file preparation, to central powder supply, to the AM build process, to heat treatments and quality assurance. Even the part removal process has been automated with the mechanical separation of parts from the build platform.

The full system comprises an EOS M 400-4 quad laser printer as well as a driverless transport system and robots that ensure the seamless production of parts from start to finish. The system is controlled by a centralized, autonomous control station that networks all the elements of the AM system. Once order data is sent to the control station, it automatically prioritizes the build requests and initiates builds on the networked additive manufacturing system.

The control station also enables users to monitor the manufacturing process remotely and compiles quality reports once the production is complete. The data needed for the production of a digital twin can then be assessed, allowing for complete traceability.

HP Multi Jet Fusion

HP expects automated assembly will arrive soon, with industries seamlessly integrating multi-part assemblies including combinations of 3D printed metal and plastic parts. As automation increases, HP proposes a vision from the industry for a more automated assembly setup where there is access to part production across both metals and plastics simultaneously. This could benefit the auto industry by enabling manufacturers to print metals into plastic parts, build parts that are wear-resistant and collect electricity, add surface treatments and even build conductors or motors into plastic parts.

HP's Multi Jet Fusion systems were developed to be highly automated in combination with the post-processing units for part cooling, powder handling and powder recycling. The newest HP Jet Fusion 5200 Series 3D printing system comes with a new cooling module, which further streamlines and automates the production process.

The low-cost cooling unit essentially sits on top of the build unit and once the printing process is complete, the still-hot parts are automatically transferred into the cooling boxes so that the build unit is liberated for the next job.

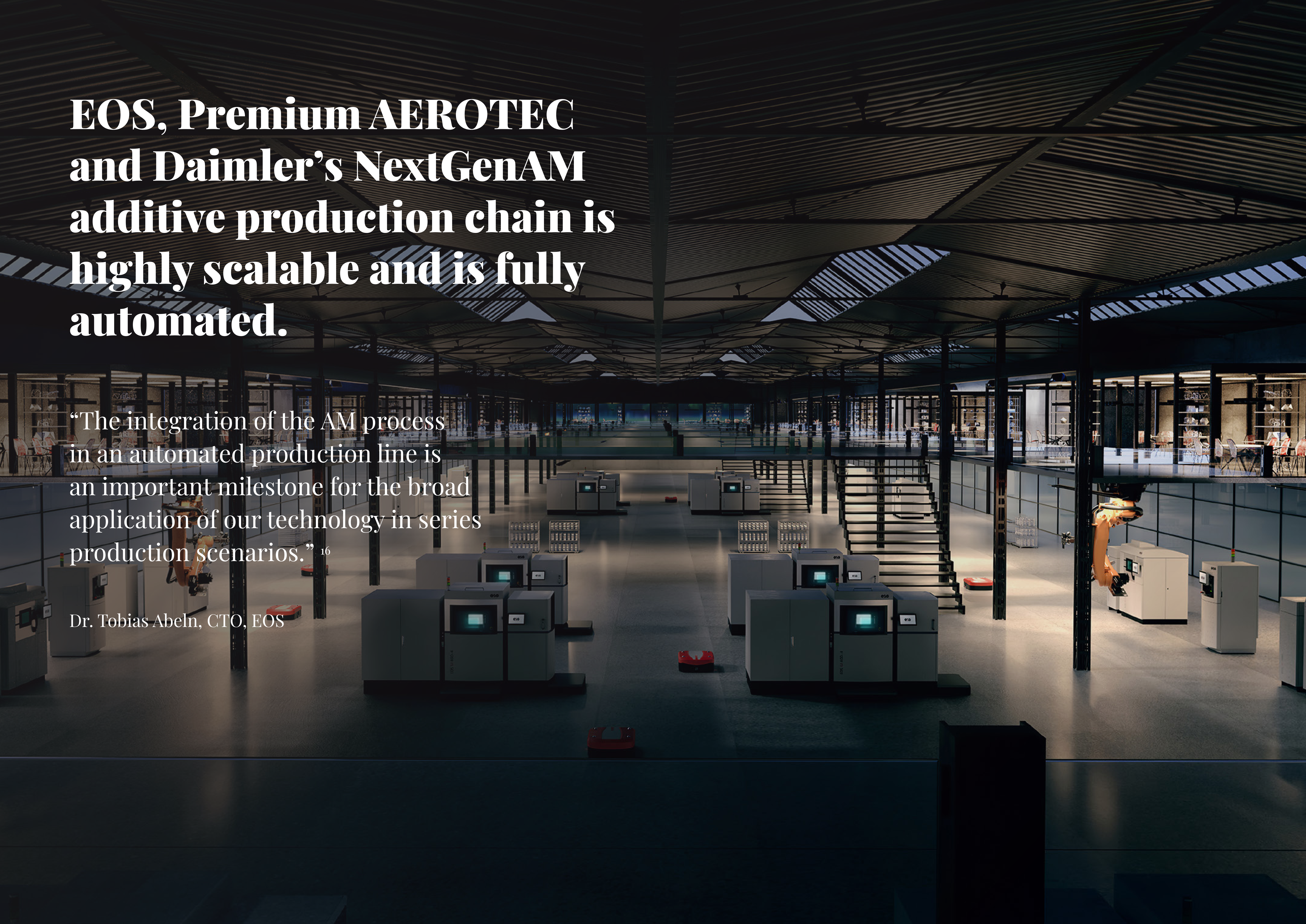
HP's MJF systems were developed to be highly automated in combination with post-processing units for part cooling, powder handling and powder recycling.[15]

3D Systems DMP 8500 Factory and Figure 4

3D Systems' vision for the metal AM factory of the future centers around the latest DMP 8500 Factory Solution metal PBF system, which the company describes as "the first truly scalable, automated and fully integrated metal additive manufacturing solution."

The DMP 8500 is a modular solution, in that it is made up of several different systems that make up an automated workflow, supported by 3D Systems' 3DXpert software solution. Each module is designed to maximize efficiency by optimizing utilization. Customers can configure a custom metal AM factory for the scaled production of precision metal parts by choosing the right combination of modules to optimize their specific production application.

The Printer Module (PTM) is capable of 24/7 operation. It is the heart of the repeatable, scalable automated solution. Its 3DXpert-driven three-laser scanning system and fast bidirectional recoater enable the rapid printing of large, seamless parts. The Removable Print Module (RPM) is an integrated unit for building parts and transporting them, as well as powder, to other modules. The parts and powder are sealed during transport and the design



EOS, Premium AEROTEC and Daimler's NextGenAM additive production chain is highly scalable and is fully automated.

"The integration of the AM process in an automated production line is an important milestone for the broad application of our technology in series production scenarios." [16]

Dr. Tobias Abeln, CTO, EOS

enables full powder traceability.
The Powder Management Module (PMM) extracts unused metal powder from build platforms, recycling the powder and preparing the RPM for the next build. The Transport Module (TRM) is designed to efficiently move the Removable Print Module between modules. The Parking Module (PAM) has an inert environment for storing Removable Print Modules until they are ready to move to a free slot on a printer or powder management unit, enabling a continuous production cycle.
At the core of 3D Systems automated AM factory vision for polymer part manufacturing is the Figure 4 platform, which is intended to transform the production of mass-customized and complex end-use parts while meeting durability and repeatability requirements of production environments. Built to be scalable, modular and fully automated, the platform allows customers to tailor configurations and select materials to address specific applications. Configurations range from single-print engine machines to fully automated, high-volume production systems with 16 or more print engines, automated material delivery and integrated post-processing.

The Production System for metal AM is at the core of Desktop Metal's automated factory vision.[17]

Desktop Metal

Desktop Metal's automated factory vision revolves around its Production System. Powered by Single Pass Jetting technology, the Production System is a metal 3D printing system, envisioned specifically for mass production, with speed, quality and cost-per-part that are able to compete with traditional manufacturing processes.

The Production System, which is designed to print a broad range of alloys, including reactive metals such as titanium and aluminum, enables the use of metal powders that are 80 percent lower cost than laser powder bed fusion metals, delivering parts at 1/20th the cost.

Designed around the MIM chemistry and powder supply chain, the Production System allows access to a large and established ecosystem of low-cost, high-quality alloys with a mature supply chain and well-studied controls.

Digital Metal

Introduced in 2013, Digital Metal's high precision metal binder-jetting technology has already enabled the production of more than 300,000 components. Now the company is focusing on automating the process for even greater throughput capabilities. In the Digital Metal vision, the majority of the process steps will be handled by a robot, which will eliminate practically all manual work, thus further increasing productivity. The robot will feed the printer with build boxes and then move the boxes for post-treatment in a CNC-operated de-powdering machine combined with a pick-and-place robot. There, the remaining metal powder will be removed and recycled, and the parts placed on sintering plates. The main robot will then move the plates to the sintering furnace for combined debinding and sintering, either in batches or for continuous production.

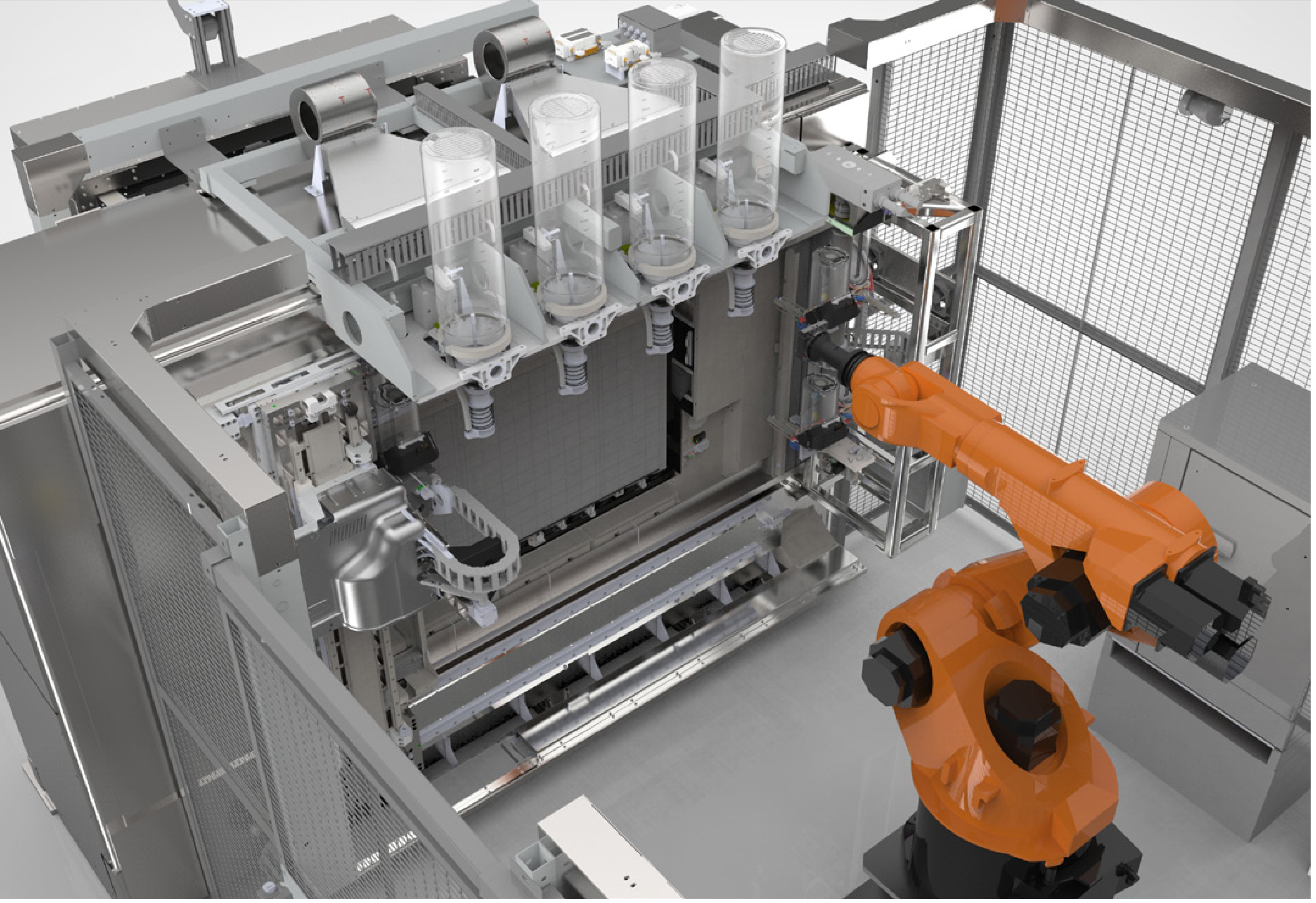
The Digital Metal vision also introduces automation during the powder removal process as an initial step towards full no-hand production. During de-powdering, the CNC-controlled movements are based on the information from the printing process. All removed powder is collected and recycled without any degeneration of properties.

Stratasys Demonstrators

Polymer AM market leader Stratasys is working on three different solutions which look toward further automation of FDM (thermoplastic extrusion), its end-use part production AM. By comparison, its advanced polyjet technology is seen (and expected to remain for the foreseeable future) primarily a prototyping process.

Stratasys production automation focuses on different automation capabilities, either through 3D printer farming or through the use of multi-axis robots with extruder heads, even working together with other robots as part of an automated industrial ecosystem.

The Continuous Build Demonstrator is a modular, automated FDM 3D manufacturing system with interconnected, high-throughput capabilities. It is designed for reliability and repeatability at scalable



Stratasys' Infinite-Build 3D Demonstrator for large thermoplastic parts and tools.[18]

volumes, enabling continuous build production and high part quality. The "Print engines" can be run concurrently on the same part type or each one can be set to work separately. The Infinite-Build 3D Demonstrator flipped FDM 3D printing technology on its side to create strong, custom parts and tooling at unlimited lengths.

From an automobile armrest to an entire aircraft interior panel, the Infinite-Build delivers large, lightweight thermoplastic parts with repeatable mechanical properties. In order to do this, it employs a multi-axis Kuka robotic arm, wielding an extrusion head. The system is programmed for automation and to be part of an automated production line with support from Siemens.

With the Composite 3D Demonstrator system, Stratasys sought to introduce a greater degree of automation to both 3D printing and composites-based manufacturing. It does this by developing a continuous layer approach made possible by an extrusion head built on an eight-axis Kuka robot and Siemens' software. Free from the layer-by-layer approach of previous additive technologies and the limiting processes of conventional composites production, the Robotic Composite enables precise material placement for maximized part strength and build speed. And with no need for support material, post-processing labor and lead-time are reduced, as are the processing steps.

Carbon's SpeedCell

Carbon SpeedCell is a system of connected manufacturing unit operations that enables repeatable production of end-use parts at any scale. The M and L Series printers, along with the automated Smart Part Washer, are part of a series of modular offerings that allow a wide range of industries to design, engineer, make and deliver end-use parts with a single manufacturing workflow.

The system is driven by a proprietary automation software that brings hardware and materials together into an easy-to-use system. The built-in DSM physics engine optimizes each print for speed, accuracy and repeatability. The data-centric approach enables the implementation of a predictive service and dashboards that allow users to monitor their printer fleet.

Carbon also uses a proprietary cloud-based Finite Element Analysis tool to help customers re-imagine their parts outside the boundaries of injection molding. As in any connected device, the software is also continually improving with one-click updates.

SpeedCell achieves superior production workflow and output by integrating multiple key operations, including part printing and part washing, to facilitate cost-effective part production. The system also features multiple Carbon Connectors, which enable hardware extensibility to support additional system capabilities in the future.

DMG Mori Path of Digitization

Digitization and automation, including AM, are key areas of development for DMG Mori. The company just introduced both an SLM 3D printer (a result of the recent acquisition of a majority stake in SLM system manufacturer Realizer) to add to its Lasertec 65 DED metal AM system as part of an entire ecosystem for automation.

The company refers to this ecosystem as "Path of Digitization" as it pursues a consistent strategy that revolves around its CELOS automation software tool, starting with the CELOS Machine and on to CELOS manufacturing right through to the digital factory. Within the latest CELOS version, new apps such as CELOS CONDITION ANALYZER or CELOS PERFORMANCE MONITOR have laid the foundation for the optimization of workflows and processes directly in the machine environment.

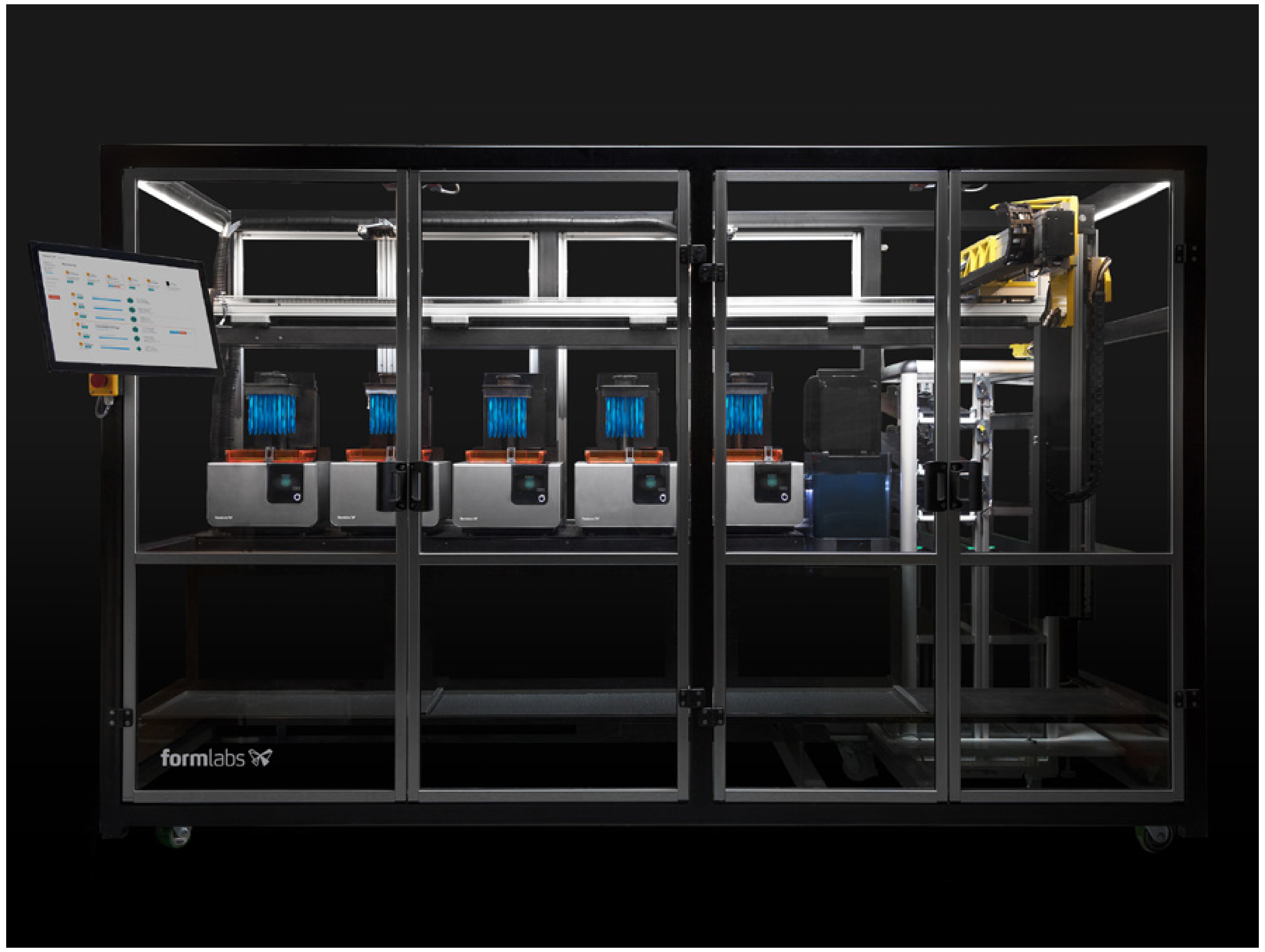
DMG Mori wants to meet cross-sector demands on cost-efficient and reliable production with coordinated automation solutions.[19]

Formlabs' FormCell

Further demonstrating how relevant automation is expected to be at all levels of the 3D printing value chain, affordable stereolithography 3D printer manufacturer Formlabs launched its own automated factory vision (together with a new benchtop SLS system) back in 2016. Formlabs' FormCell was developed to automate the most repetitive parts of the 3D printing process. The company addressed this issue by providing an automated 3D printing solution that leverages the Form 2 desktop 3D printer within a scalable cell of 3D printers that aligns and automates repetitive 3D printing processes, enabling a 24-hour digital factory.

The system includes a row of 3D printers, a post-processing solution, and an industrial robotic gantry system, plus software to optimize print scheduling and API endpoints for industry-standard business systems and homegrown systems alike. Because the Form Cell is built around affordable hardware, it is possible to prove ROI in months, rather than years. ◆

Formlabs' FormCell leverages the Form 2 desktop system within a scalable cell of 3D printers and enables a 24-hour digital factory.[20]

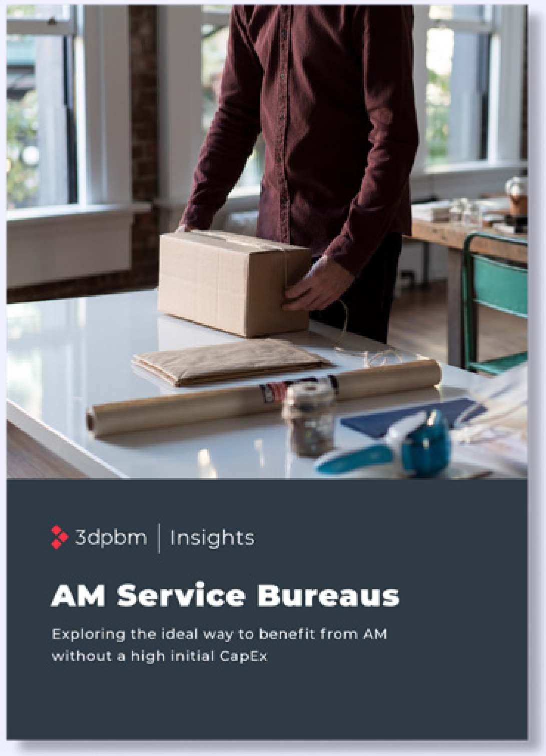


UPCOMING EDITIONS

AUGUST AM Service Bureaus

AM service bureaus play an integral role in the AM industry. In this segment, we showcase how they provide access to 3D printed parts to those who may not have the resources to install the technology, and are well positioned to encourage AM adoption across various industries.

- Analysis
- Interviews
- Case Studies
- Mapping



SEPTEMBER Dental AM

The dental segment has been a critical driver of AM adoption. Today, dental labs across the world are using AM to improve patient care and streamline production.

OCTOBER Metal AM

In this segment, we not only analyze the current state of metal AM for industrial applications, but also where the technology, in all its iterations, is headed.

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Spotlight

Going with the AM-Flow

The transition to automated additive manufacturing workflows is inevitable and challenging. This Dutch company is here to make it flow smoothly.

AM-Flow has brought to market a series of automated post-processing solutions to create the first AM production lines.[21]

Ever since 3D printers began the paradigmatic shift from stand-alone rapid prototyping machines to networked units within production workflows, it became clear that additive manufacturing—the most digital among manufacturing processes—was also the least automated and the hardest to integrate into full end-to-end production workflows. By comparison, injection molding—the least digital of all manufacturing processes—is much more integrated and remains a better fit for mass production. And although additive manufacturing does not intend to become a full replacement of injection molding, for additive manufacturing to be a realistic manufacturing technology choice it still needs to become more competitive. And one way of becoming more competitive is to automate all post-processing steps after printing. AM-Flow has set out to deliver post-processing automation solutions, to create the first AM production lines in the world.

One of the reasons why it is so hard to integrate AM into large volume production lines is precisely its digital nature. The idea of "digital" manufacturing would seem to imply a perfect fit within automated production but it's actually quite the opposite. One of the key advantages of digital manufacturing is that every single unit in a batch can have a different geometry. This means that any successive system within the workflow has to be able to recognize an individual part exactly for what it is. This has not been possible until recent advancements in machine vision and AI, enabling high mix AND high volume. Now a solution exists: the path to full AM integration into a large volume production workflow is still a very complicated one, but the rewards are going to be significant. And the alternative is none.

Learning to automate

The team behind AM-Flow gained much of its initial experience in AM production while building and running Shapeways. In 2014, this writer had the opportunity to visit its New York factory and, while it was a fascinating experience to see all those EOS production machines churning out parts, it was also shocking to see the manual labor that went with sorting, cleaning and packaging the printed products for shipping out. Since then, leading AM services have dramatically expanded their machine park. Today full workflow automation is no longer just an option but a prerequisite to be able to scale the business. That's where AM-Flow came in.

"What proves really difficult in AM compared to other industries is the freedom of geometry," begins Stefan Rink, Co-founder and CEO of AM-Flow. Mr. Rink's background is in using IT and Lean Six Sigma to analyze and automate bottlenecks in industrial processes, first in metal construction and then in the solar power industry. "Every part is different. AM service bureaus are particularly challenged as they face an extreme mix of geometrical shaped 3D parts and high volume orders coming in on a daily basis. At Shapeways, for example, it's impossible to predict what customers are going to order, with on the one hand a huge B2B customer base and on the other hand over a million community members using the platform globally."

AM-Flow was founded to address the challenge of full workflow automation in the additive manufacturing process.[22]

"Live up to the promises of freedom of design, local manufacturing, short lead times and minimal logistics."

Production-ready systems such as the EOS P 796 or HP's 5200 series machines can output up to a thousand parts in a single batch. A lot of manual labor is required to sort out that kind of volume. "When I started in additive manufacturing I had the privilege of working with a highly educated team," points out Rink, "but the more we optimized our 3D printing processes, the duller most of the tasks became: in the end, it comes down to recognizing a part, putting it in a plastic bag and walking parts through the factory. Really simple tasks. It wasn't becoming an interesting place anymore for engineers and we see this happening around the 3D printing world.

"Add the continuous pressure to lower price per part (still 5 to 10x the price compared to injection molded parts) and then you have only one choice," Rink adds. "Either move your AM factory into a low-wage country or start automating the workflow and get it interesting again. We luckily did the latter and that should be the approach of the AM industry as a whole. Live up to the promises of freedom of design, local manufacturing, short lead times and minimal logistics. The increasing number of successful applications designed over the last 30 decades have resulted in lots of parts being 3D printed today in numerous factories all over the world. For investments in those factories to pay off, the cost profile per part needs to change. If you do the math at mature factories, manual labor costs greatly outweigh machine depreciation and raw material cost.

How does AM-Flow help achieve this? By providing a full stack of solutions that integrate all—or almost all—segments of the AM production workflow, both at a hardware and software level. It all starts by being able to identify 3D parts based on their geometry with the AM-VISION. Now that you can identify parts, you can sort parts into bin for their next process step, whether it's being sent directly to the distribution center (DC) for shipping or being sent through to other routing steps like polishing, vapor smoothing, dyeing or assembly, and then finally to bring all parts of a single client order together for packaging.

The AM-Flow network

"The 3D printing industry can learn a lot from the other industries," Rink explains. "For example, automated picking and placing, tracking and tracing, transportation and packaging. The big difference is in the individualized geometries and the fact that you don't have a limited, standard product library with common product ID labels. That's what we started solving: we can now identify parts in a split second based on the geometry alone. In order to do this, the AM-VISION compares each printed part with the original STL file. It looks very similar to an airport scanner, with parts flowing on a conveyor belt.

"That's where our magic happens," Rink continues. "We are aiming for fully automated production lines. Every machine, every module we put into the market has an input and an output based on a conveyor belt, making it fully modular. With the AM-PICK robot we can go from batch to one-piece-flow and back again." This enables clients of AM-Flow like BMW, Midwest Prototyping, Shapeways, Materialise, Marketiger and Oceanz to connect AM-Flow's proprietary modules in different layouts and integrate external systems such as cleaning and part quality enhancing post-processing hardware, e.g. provided by specialized firms like DyeMansion, AMTechnologies, PostProcess or AM Solutions. At the same time, the AM-Flow modules work with currently available MES (manufacturing execution systems) software such as Materialise's Streamics, 3YourMind, Authentise, Link3D, AMFG, Siemens NX, Oqton or any of the other third-party MES or ERP software prgrams like SAP, Oracle or Microsoft Dynamics.

On the touch screen operator consoles AM-LOGIC runs. It is used to show the operator a reduced amount of information necessary to complete tasks effectively, based on contextual, visual information provided by the ERP and MES. "We are aiming at a fully automated system, so there should be very little information running through the AM-LOGIC console," says Carlos Zwikker, Commercial Director at AM-Flow. "Most of the time the process is running automatically."

"This is Industry 4.0, so you always need connected solutions," Zwikker, points out. "The logic of how a part moves through a 3D print factory is managed by the MES or ERP, the backbone of every digital factory. We provide the recognition, sorting and routing of the printed parts, where the MES software tells us which printers the parts are coming from and where they need to go next: to post-processing or to be packaged and shipped to the end customer. This way we can provide a full 'track & trace' process for AM production lines."

This is a key element because it enables manufacturers to automatically track every single step of the process. A prerequisite for ensuring high quality standards and essential if you want to provide as an additive manufacturer to industry segments like aerospace, medical, defense and automotive, that have strict certification requirements.

Overall, the AM-Flow solution stack includes six modules: AM-VISION for part identification, the AM-LOGIC touch screen operator console, the AM-SORT high-speed gentle touch part sorter, the AM-PICK robot arm for part handling, AM-ROUTE mobile robot (AGV/AIV) and AM-BAGGING for automated bagging and labelling. All AM-Flow modules are designed to be capable of dealing with infinite geometries. AM-PICK for instance comes with a special gripper that can pick many of the delicate and constantly changing geometries.

Automated AM workflow processes have become increasingly critical in the face of COVID-19, which has disrupted supply chains and normal production rates.[23]

"When developing our solutions we have three design rules." Rink clarifies. "First, at launch a module is able to process over 90% of the parts in a fully automated way. Second, the throughput time per part is below five seconds and, third, the new machine has a solid, profitable financial business case from day one".

All AM-Flow modules in the market are showing stable performance levels in the high 90%, are able to meet the low takt time requests expected at automated production plants and lowering the cost per part. And don't forget about returning the fun factor to the workfloor!

Dealing with the infinity of possible geometries is an uphill battle. In that sense AM-Flow will never be finished. The team is applying the latest state-of-the-art AI and machine learning. Processing thousands of parts on a daily basis helps identify edge cases and solve them continuously. This way AM-Flow is working together with the operators of its customers to provide a seamless production line performance and get closer to the perfect digital factory every day.

Automating AM factories now

The COVID-19 crisis highlighted the need for shorter supply chains and dramatically accelerated the trend towards automation. Both of these play into the vision for more automated additive manufacturing. But the question remains: how fast can it be implemented? "Factories have a huge backlog now," says Dennis Lieffering, AM-Flow works with a number of customers, including BMW, Midwest Prototyping, Shapeways and Oceanz.[24]

Marketing Manager at AM-Flow. "Social distancing has to be taken into account while operating factories around the clock. In order to do this, everyone is working overtime: within this context, our systems could increase productivity by a factor of 5 to 10X."

The endgame is to make AM competitive against injection molding, with the added benefits of shorter lead times and increased geometrical freedom. The factors keeping the cost of AM high are no longer machine and materials prices. Machine expenditures have largely been absorbed by service bureaus and industrial adopters in the past decade. Materials prices will come down as demand increases. So, paradoxically, the biggest limit for AM today is the cost of human labor for repetitive tasks. "The pandemic has shown how dependent we have become on very long supply chains," Lieffering continues, "companies don't want to rely on that long chain. It's too fragile. We have to come up with local production. But the 3D printing environment isn't completely ready yet. Now, the key question is: are companies going to actually make a decision based on these observations?"

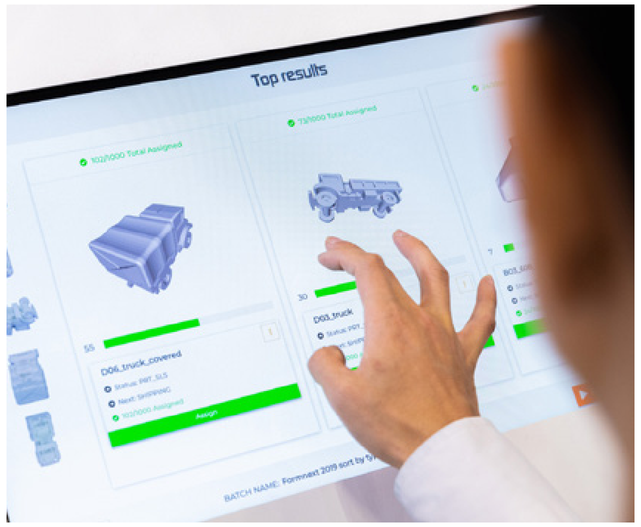
One key driver for the automation of AM is the internalization of AM production by large industrial adopters. For these large companies, such as BMW, one of AM-Flow's first customers, automation is already a fundamental aspect of their production workflows. "Five years ago, 3D printing service providers were doing the largest volumes," says Zwikker. "Right now OEMs are printing large volumes. Companies in automotive and aviation are not just producing more parts but also a very high mix of parts. That surprised us at first and we found that the reason behind this is the combination of parts production and very intensive functional prototyping.

These companies are literally printing tens of thousands of different parts to showcase internally and now they are extending this to direct production. For them automation is a given: they just need to add AM to their automated workflow environments.

Growing with the AM industry

In close collaboration with key software and hardware providers, AM-Flow delivers a complete end-to-end hardware and software solution stack, covering every step of the process. A lot has been achieved in the market over the last three decades with a primary focus on the 3D printing technology itself. Now is the time to broaden the scope and look at the AM Factories. Today, both for polymer and metal printing it's about the economics. And the key to unlocking competitive price levels per part lies in factory automation. "We support over 60 different materials and finishes, including both metal and plastic parts," Rink explains. "In particular

AM-Flow delivers a complete end-to-end hardware and software solution stack, covering every step of the process.[25]



we have been working with one of our customers, Midwest Prototyping, on materials and part handling. They specialize in being able to offer as many different materials and finishes as possible, providing high quality parts, so this collaboration enabled us to expand our material library significantly."

Automating the post processing of additive manufacturing is complex and requires a broad collaboration. AM-Flow's Eindhoven office is located inside the Brainport Industries Campus (BIC), a 100,000-square-meter international campus development in Eindhoven with technology, education, authorities and facilities united under a single roof. Neighboring companies include Siemens; Additive Center, helping companies with application development; Marketiger, leading provider of full color prints; as well as K3D, a metal printing technology center using the Metalfab1 technology of Additive Industries. This Dutch AM hardware OEM has made full automation one of the primary objectives of its modular printing systems and its vision is highly synergic with AM-Flow's.

"Fortunately," Zwikker concludes, "we have great technology partners and very forward-thinking customers, who understand that they need to get into a learning curve on how to incorporate automation. It's also easier to do this when the industry and the factory teams are growing, rather than later on. To help beat corona and summer staffing challenges, we offer the first five companies who will reach out to us—and mention this article—free use of the set of AM-VISION, AM-SORT and AM-BAGGING for two months, to help them take the first difficult steps on this learning curve." ◆

Case Study

Automating automation systems

How Schubert’s PartBox is using 3D printing to automate spare parts production on its automation systems.

Founded in 1966 in Crailsheim, Germany, Schubert’s automation solutions are used by widely known brands such as Ferrero, Nestlé, Unilever, and Roche.[26]

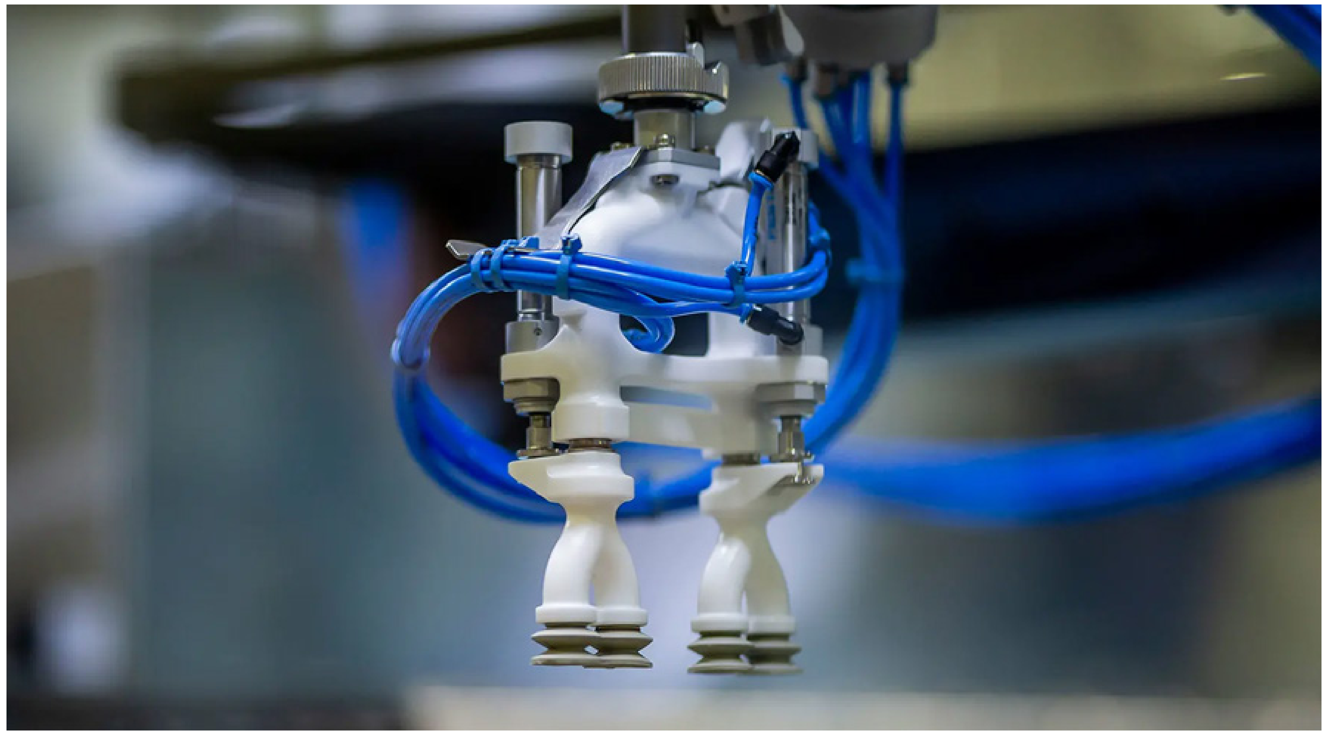
German firm Schubert has been making automation systems since the 60s. Today the core of its business is represented by the TLM systems, which are state of the art packaging machines. In other words they represent the ultimate and final step in mass production automation. Foods, drinks, consumer products: everything that can be packaged goes through these machines at very high rates. And sometimes parts need to be modified or replaced.

Because these are often very specific and complex types of parts, 3D printing has proven to be an efficient solution for internal use at Schubert. In fact, the company has 3D printed over 100,000 single parts since 2014, in 6,000 different part types. Today the company is printing nearly 50,000 parts per year, using SLS, FDM and SLM technologies, either internally or through partner service providers.

“We have been using 3D printing so much for our own spare and replacement parts that we decided we wanted to make this technology readily available to our customers as well,” says Conrad Zanzinger
Technischer Leiter / CTO at Schubert Additive Solutions GmbH. He runs the AM operations at the company. “That’s why we created PartBox.”

PartBox is a Digital Warehouse for spare parts. It holds the designs of several parts that may need replacement and enables Schubert’s

Schubert is printing nearly 50,000 parts per year, using SLS, FDM and SLM technologies, either internally or through partner service providers.[27]



customers to 3D print them just by pressing a button, either from their computer or even a mobile phone. It does what several other third party software providers, such as 3D PrinterOS and Authentise, for example, are helping companies implement. However, it is a closed system developed by Schubert for its customers.

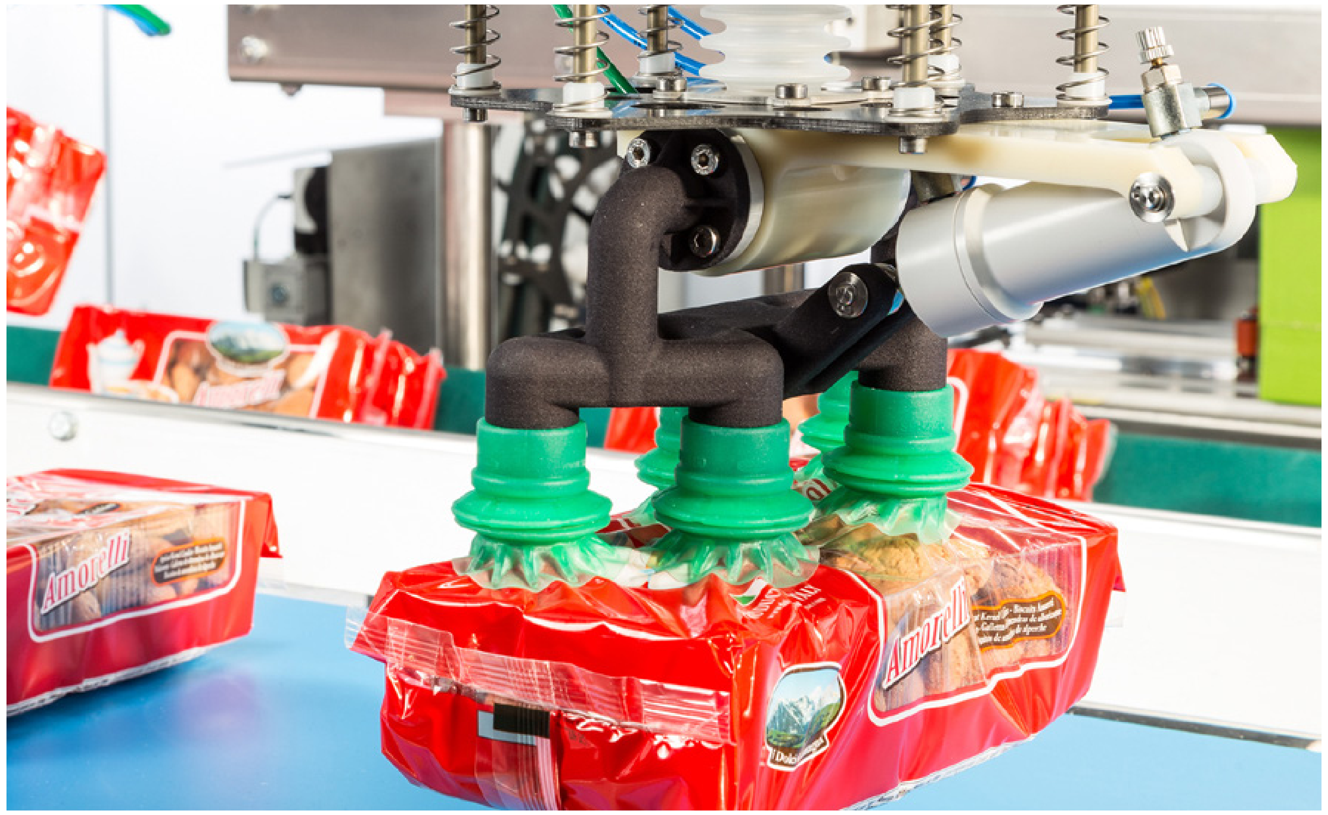
Although Schubert has used other AM technologies for its internal needs, PartBox leverages Ultimaker 5 3D printers exclusively. These machines have come a long way since the early desktop versions and can now support up to five different materials, with a high degree of automation in material supply. All technical specifications have been integrated into the Schubert PartBox software. “Many of our clients were not familiar with 3D printing before we presented this solution to them. They usually don’t have time to play around with slicers and filaments. So we needed to make this system as readily accessible as possible. We have taken care of everything for them. All they need to do is select the part they need, select an available printer from the queue and press print,” says Zanzinger.

For Schubert this has proven to be an extremely efficient solution. In the past, having to ship a part may have required several hours and even days of downtime. With 3D printing, it’s possible to simply send out a digital model and produce it on location. However Schubert needs to retain control of the model and the printing process. “With PartBox we wanted to ensure the easiest operation, with the simplest hardware and the lowest initial investment,” Zanzinger says. “The system today requires no programming and it is able to guarantee reproducible quality along with the highest level of data security.” With PartBox, the end users are not able to modify the model. They stream it to their printers and Schubert can get paid for each part that its customers need. The complete hardware and software package includes the Ultimaker 5 3D printer, a GS Gate IoT server platform for secure streaming and the part streaming software platforms.

The key elements in a packaging machine are the tools used to grip thousands of different types of parts. Although this is not as complex as having to recognize each single different part (as in AM-Flow’s case), it still requires thousands of different tools tailored to rapidly and efficiently handle the specific requirements of a particular product. In one application case, Schubert needed to replace a gripper for a small plastic cream container. The traditional gripper was made of 192 turned parts, 18 complex milled parts, 1,024 screws and required one full day to assemble. With 3D printing, the same part is made of 0 turned parts, 0 complex milled parts. It only has 8 screws and takes 10 minutes to assemble. This is one example, but PartBox also includes a number of machine spare parts, jigs and tools as well.

The PartBox Digital Warehouse is an incredible improvement compared to current messy physical warehouses. A single 3D printer—or 3D printer farm—can replace dozens of shelves and boxes. Integrating 3D printers into a fully automated production workflow may still take several years, but using 3D printers to keep current automated mass production systems running is already a reality. ◆

A single 3D printer—or 3D printer farm—can replace dozens of shelves and boxes in a warehouse.[28]



Interview

The one-stop automation factory

Siemens VPs Karsten Heuser and Aaron Frankel help us put together the pieces of the infinitely complex AM automation puzzle.

"The fundamental barrier companies face with scaling up AM for industrial production is a disjointed AM process chain," says Aaron Frankel.[29]

The list of products, services and concepts that Siemens is offering to clients working to implement an end-to-end production workflow revolving around the additive manufacturing process is almost endless. It has to be, in order to address the extreme complexities of the AM process itself and everything that comes before (design) and after (post-processing and product lifecycle). Mapping out the entirety of Siemens' solution can be just as challenging. As part of this exclusive eBook on AM Automation, we asked the two people in charge of leading this transition to help us understand exactly how the Siemens ecosystems works. In this exclusive interview, Karsten Heuser, VP Additive Manufacturing Siemens Digital Industries, and Aaron Frankel, VP Additive Manufacturing Software Program, explain how they are able to provide an overarching structure that contains all the elements of the automated, end-to-end, additive manufacturing workflow, from digital part design to the digital warehouse.

Xcelerating additive

Today, Siemens Xcelerator platform offers an integrated end-to-end AM software solution that spans the entire additive process, from idea to finished part. This solution provides capabilities for a myriad of processes, from order management to design and simulation of AM parts, Siemens uses various automation tools to industrialize production of printed parts at their own facilities.[30]

generative engineering, build preparation with simulation for first-time-right printing, post-processing and quality assurance, AM factory planning, manufacturing operations management, digital thread management, and performance analytics. These capabilities are provided through NX, Simcenter, Tecnomatix, Opcenter, Teamcenter, MindSphere and Additive Manufacturing Network product lines.

"The fundamental barrier companies face with scaling up AM for industrial production is a disjointed AM process chain," Frankel explains. "Using multiple disparate software applications disconnected from production equipment that can only communicate via data translations, STL files and network file folders is highly inefficient, untraceable and error prone. Without an end-to-end AM solution that leverages a common data format in a single environment, companies cannot maximize the cost, timing and transformational benefits of additive manufacturing."

In order to simplify and streamline all these processes, Siemens AM software and partner products interact within a managed environment, where data, processes and collaborators are connected via a single digital thread. Siemens products are open, which means that third-party software and hardware providers can integrate, automate and optimize their technologies in the digital value chain.

"Customers can leverage the best of Siemens and partner capabilities to achieve much more efficient idea-to-AM part delivery, increased product functional performance, elimination of failed builds and quality parts faster," Frankel explains. "The Siemens integrated AM solution offers seamless interaction throughout the additive manufacturing process. A design change made at the beginning of the AM process can flow smoothly into engineering validation, build preparation and process simulation. This tight integration is what allows for more streamlined AM processes, greater automation opportunities, first-time-right 3D printing and full lifecycle traceability."

This holds for the printer hardware as well. While hardware companies have been working hard at improving the mechanics of the process, the connection from software to hardware remains an issue. Siemens provides AM software, but also controllers that are used in AM hardware. "So our communication thread can run seamlessly from the front-end design through to the shop floor hardware," Frankel adds. "This is a critical connection companies must establish to realize true industrial additive manufacturing."

Third party factory

Leveraging an open API approach, Siemens software can connect to a wide range of 3D printer software, post-processing equipment software and other services like data and IP security. This ecosystem of AM partners includes numerous industry leaders around the globe and continues to grow.
"At Siemens, we realize that we cannot develop every solution for our customers by ourselves, which is why we continue to expand our ecosystem of AM partners," Frankel clarifies. Siemens software partners today include AlphaStar, Identify3D and Materialise (also a leading AM service provider), as well as several AM hardware manufacturers from all over the world, such DMG MORI, EOS, HP, Stratasys, Trumpf, Renishaw, Shining3D, Hanbang, Desktop Metal, Markforged, SLM, GE Additive, BeAM, Evolve, that also develop software for their systems.
Since Siemens owns software products across the AM process chain, the company's overall focus has been on offering an integrated solution to facilitate the most complete and efficient digitalized process possible. "Whenever we have found a third-party solution that we think fits within our product suite, we have worked to either purchase or integrate that solution so that the end-to-end AM digital thread remains continuous," Frankel says.

This is evident from earlier collaborations, where companies like EOS and Renishaw integrated their software with Siemens', and with purchases of specific software solutions, like the late-2019 acquisitions of Atlas3D, for build orientation simulation, and Multimechanics for microstructure optimization. Next up—Frankel revealed—is the integration of the CURA solution from Ultimaker to expand to and connect with desktop printing hardware.

Digital twins and digital warehouses

Digital Twin is particularly important in the additive manufacturing process. Not only do industrial AM adopters need a dynamic Digital Twin of their AM product, but it's essential that they fully digitalize the 3D printing process itself. Unlike traditional manufacturing processes, additive is a fledgling technology.

Establishing repeatable, traceable and optimal processes for 3D printing parts at scale cannot rely on tribal knowledge or decades of conventional wisdom. A living Production Digital Twin that quickly incorporates insights is critical to the success of an AM operation.

"At Siemens we enable digital twins of the entire AM process," Frankel explains. "This means simulating the print process to remove any chance of quality issues. Moreover, it means simulating the operations of the entire AM factory and performing what-if scenarios to ensure that companies can achieve their throughput goals.

Frankel also emphasizes that companies need a Performance Digital Twin, leveraging IoT data analytics, not only to capture the production process in operation for continuous improvement, but also to monitor the performance of the products themselves when they reach customers.

On the other hand, the Digital Warehouse concept is one of many use cases that Siemens recognizes and supports primarily for additive manufacturing. "The ability to produce parts on-demand through distributed manufacturing is absolutely a driver for a segment of our customer base," Frankel says.

Materials Solutions, a Siemens business, prints parts, but also post-processes and inspects them in-house.[31]

The use of design, simulation, and manufacturing automation tools is what allows Siemens to produce highly complex printed parts at scale.[32]

As a practical example, Siemens' partner Big Metal Additive just demonstrated a transport system for use by the US military that can be produced in the theater using their large-scale additive manufacturing system and Siemens software.

Holding the strings

The vision for how software, hardware and control systems work together to enable an actual production workflow makes sense. But Siemens is fairly unique in the global market as both a software and hardware vendor to the AM industry. How exactly does this translate on the factory floor? How does software move materials, machines and parts? "The end-to-end AM workflow is controlled by our customers and partners," Heuser tells 3dpbm. "We just deliver the software and hardware tools to support them in the workflow. This covers both the AM software digital thread as well as the hardware thread that supports that digital process. The physical aspects of manufacturing, such as material handling or part handling can also be simulated and tracked through our Opcenter solutions."

In other words, as Siemens' controls power AM hardware, Siemens' software tools allow customers to create a digital twin of both the part being printed as well as the process being utilized. This digital twin includes not just design, but also simulation, post processing, and even shop floor management within NX, Simcenter, Tecnomatix and Teamcenter solutions.

“Automation needs to be tailored not only to the technology, it needs to adapt to the industry and business model”

Siemens is not a machine builder but more than 60 machine builders industrialize their machines with Siemens automation technology, in all relevant technology fields. “We help machine builders to industrialize their machines to improve quality, uptime, throughput and productivity,” Heuser continues. “A portfolio called Totally Integrated Automation covers IPC, Drives, Motors, Controls for multi-axis movements, industrial Edge hardware and AI software technology stacks. Furthermore, we have integrations in the end-to-end workflow from software into the machines. And we’re also working on connectivity of the machines in Monitoring and Cloud solutions.”

Siemens’ key partners in this effort include DMG Mori, EOS, HP, ExOne, Optomec, BEAM, Farsoon, Electroimpact, Stratasys and many more. “When it comes to additive, successful companies can’t exist in a vacuum, so a robust partner ecosystem is key,” Frankel adds.

“Knowledge about the AM process is spread across enterprises, startups, hardware OEMs and even research institutions. We absolutely have a robust partner ecosystem on the hardware side that includes AM machine OEMs as well as consulting, material and production companies. Partnering is key to achieving the end-to-end additive solution that Siemens is working towards.”

The quest for full production automation

“Automation needs to be tailored not only to the technology, it needs to adapt to the industry and business model,” Heuser points out. “For example, automation is different for a digital warehouse production or individualized products in Lot size 1 versus serial parts. All technologies can leverage automation, where feasible. In Powder Bed Fusion, for instance, powder removal can be automated. In fact, Siemens worked on a project with German AM post-processing leader Solukon to evaluate the value of just such a solution.
The maturity of automation is very different and heterogenous in different companies and industries. Siemens Energy itself is very mature in serial production. However, we don’t believe there is a final end state for automated AM production. Just as with conventional production, automation optimization is a continuous journey. And that journey must be pursued within the context of a customer’s overall AM process.

“This is why we are helping more and more customers run full process simulations of their AM factories. These factory simulations will show a customer precisely when automation is feasible for their operation and when more manual processes are sufficient—all predicated on the goal of achieving their throughput requirements as efficiently and cost-effectively as possible. One example of this holistic approach to considering AM automation comes from our work with BMW. They are in the process of building a 15-million Euro AM Campus, and they wanted to explore whether their process concept would achieve throughput goals. Our factory simulation showed BMW where automation could help improve the process—and, just as importantly, where it wasn’t required.”

What emerges clearly from these experiences is that AM is vastly more complicated to integrate into production workflows than other manufacturing processes. AM requires a complete change in manufacturing mindset. Technologies and materials continue to progress at a rapid pace, but many adopting industries still lack the adoption of standards and the experience base to immediately take full advantage of it. Out-of-the-box production solutions for specific customer needs are rare – and companies need to invest in their people, processes and technology in order to gain the business advantages of additive manufacturing. “Old habits die hard, and in this case, it’s the tendency of people to do what is familiar instead of what is radical that is the impediment more than the integration of the technology itself,” Frankel observes.

“When it comes to additive, successful companies can’t exist in a vacuum, so a robust partner ecosystem is key,” said Frankel.[33]

When it comes to part production, the trick is learning how to get quality output from the additive process. This is the same learning curve that companies went through with the introduction of computer-aided machining (CAM) or robotics. However, what is different about additive manufacturing is the learning curve necessary on the design side. Not only must designers understand the new rules for designing parts but they must also understand the new possibilities for innovation that additive brings to the table.

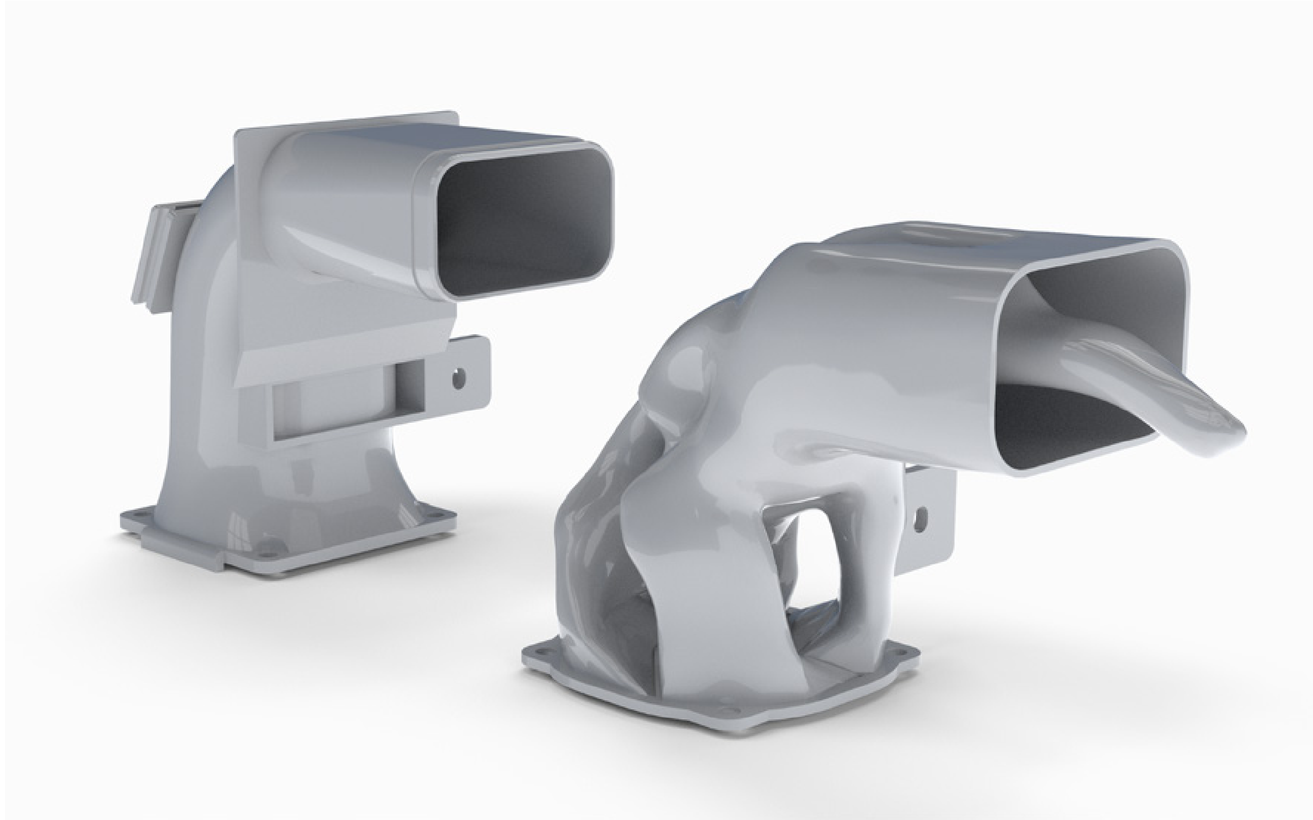
"The Siemens Power Generation team," Frankel points out, "has been exceptionally good at innovation with the possibilities of additive manufacturing. However, this is not always the case, and we often find ourselves working to encourage customers to think more creatively about part design with AM."

At the end of end-to-end

"We want AM to be 'just another tool in the tool chest' for our customers, so we are working towards a day when it will be just as easy for our customers to print 100,000 unique parts as it is to machine 100,000 carbon copies of a part," Frankel concludes. "That said, we recognize that AM is a transformational technology which, when matured into its full potential, will fundamentally change the nature of innovation itself, allowing for an unprecedented level of automated design exploration, distributed manufacturing, and product intelligence, personalization and performance. While we are absolutely focused on the day-to-day challenges of AM, we never take our eye off the ultimate vision for what this technology can bring to the manufacturing world.

The decrease in cost driven by production automation will be key in driving widespread adoption of additive.[34]

Automation tools for design and printing can facilitate the creation of geometry heretofore impossible to manufacture.[35]



"At the end, it's about production costs and throughput," adds Heuser. "Automation needs to support higher productivity and lower production costs. Furthermore, automation will be a key for EHS in terms of handling powder in the production flow." As important as automation in the workflow for software—Heuser points out—is improving the efficiency in the engineering workflow: there are actual production requirements such as automated nesting, automated serial number placement, automated generative engineering or automated part identification. As we anticipated in the article on page 48, this is what AM-Flow is working on, with Siemens as a possible partner.
In manufacturing, cost is king, and automation of production is another avenue to driving down the costs of manufacturing. So, anything that can be done to make additive a more cost-effective manufacturing solution will also drive up the adoption of the technology.

This will in turn drive down the costs further in a virtuous cycle. The more cost-effective additive manufacturing becomes, the more favorably it will compare against traditional manufacturing methods. Since cost is king, the decrease in cost driven by production automation will be key in driving widespread adoption of additive. ◆

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