



GE Additive

Path to Production Playbook

Planning a successful transition
to serial additive production

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Additive

The Path to Production

Metal additive manufacturing continues to gain momentum with many organizations starting to look at shifting to a full-scale commercial production. In this playbook we share some lessons learned on our own additive journey to help others as they take steps to shift to industrialization.

If not tackled correctly, these barriers and their key variables - machines, process, powder and parts - might derail your additive strategy.

The path to serial additive production requires careful planning, patience, awareness of potential pitfalls, and meticulous attention to detail – but, if done correctly, can also have enormous benefits, such as shorter production lead times, cost savings, consolidated part counts, reduced waste, improved sustainability and a simplified supply chain.

In this industry playbook, we share some lessons learned on our own additive journey to help others as they take steps to shift to industrialization.

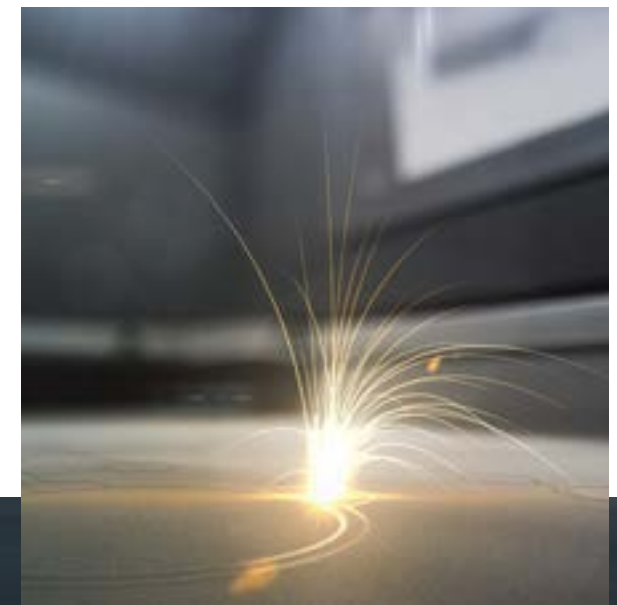
EXECUTIVE SUMMARY

Metal additive manufacturing continues to gain momentum with many organizations starting to explore the technology for the first time.

Those tentative steps still often involve prototyping or turning to service bureaus to produce one-off, difficult-to-find replacement parts. However, the shift to full-scale commercial production is another matter altogether.

Organizations embarking on the industrialization phase of their additive journeys often encounter a similar set of industry barriers;

- Part identification
- Returning investment profit
- An experience gap
- A talent or resource shortage
- Cultural resistance to change



Picture: The GE9X on a test platform at GE Aviation's testing facility in Peebles, Ohio. The GE9X is a massive high-bypass turbofan that boasts 304 additively manufactured parts spanning seven components. GE Aviation is currently mass producing these parts at its manufacturing plants in Auburn, Alabama and Cameri, Italy. Source | GE Aviation

Learning **by doing**

The LEAP fuel tip

GE Aviation's own serial additive production journey began more than 10 years ago with the re-imagining of the fuel nozzle on the CFM LEAP* high-bypass turbofan engine.

Traditionally, aircraft engine fuel nozzles were manufactured using an extensive sequence of complex parts that were brazed together to create the final form. The traditional process was low yield, low durability and didn't provide the engineers the ability to optimize the design to meet requirements.

Previously, this complex metal part was made from 20 components. Today, the fuel tip is printed as a single piece.

GE Aviation produced its first Federal Aviation Administration-certified, additively manufactured fuel nozzle in 2015. Since then, more than [100,000 fuel tips have been printed](#), reducing inventory for that part by 95% and lowering cost on the component by 30%.

PRINTED AS ONE PIECE

[WATCH VIDEO](#)

*LEAP is a trademark of CFM International, a 50/50 JV between GE Aviation and Safran Aircraft Engines

By redesigning the nozzle from scratch with additive manufacturing in mind, it has reduced the part's life cycle impact due to:

- 25% lower fuel nozzle weight, resulting in reduced fuel consumption over the life of the aircraft;
- 5 times longer fuel nozzle lifetime; and
- Lower raw material consumption due to higher materials yields in manufacturing.

Designers, manufacturing engineers and quality teams from GE Additive and GE Aviation were co-located during the part development process. This increased collaboration across the team and facilitated decision making, allowing them to quickly resolve any technical issues.



We tell the story about the LEAP fuel tip because the redesigning of that part was our "Ah ha moment," the beginning of our production journey. Once our design engineers realized they could use additive manufacturing to mass produce the part, rather than just prototypes, the game changed. We were able to throw out everything we knew about designing aerospace-critical parts and start designing to meet the industry and part challenges. We designed the part for functionality versus accommodating the traditional manufacturing process. This part was the catalyst to more and more parts.

CASE STUDY

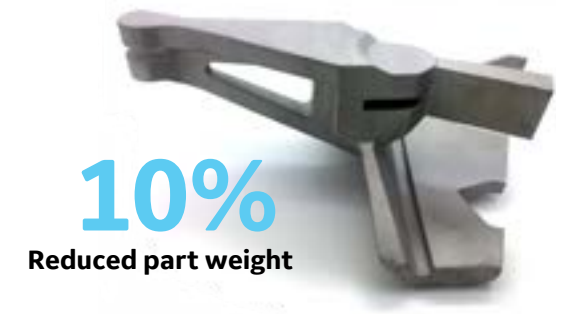
Power Door Opening System (PDOS) bracket

In November 2018, GE Aviation received FAA approval to replace a traditional bracket on the GEnx-2B engine with an additively manufactured bracket. The new bracket, used for the power door opening system (PDOS), allows the GEnx's fan cowl to be easily opened and shut for quick maintenance checks.

By using existing powder and material qualifications and data set, GE Additive and GE Aviation engineers worked closely to accelerate the process, which can take years in the aviation industry. Leveraging all of GE's best practices the part went from design to production in less than 10 months.

GE Aviation chose not to radically change the design of the PDOS bracket or optimize the design for additive. Rather, they made modifications to produce it more efficiently. For instance, they chose to use a cobalt-chrome (CoCr) alloy that already had FAA approval, and used the data set from an already-certified fuel tip and applied both to this part.

It is vital to ensure that the data you have for each material is representative of both the



manufacturing process and the geometry of the parts you are printing.

GE Additive's Concept Laser M2 machines print four brackets - an aircraft's worth of brackets - in each build, achieving one of the program goals of lowering part costs.

The results with the additively manufactured PDOS bracket have been impressive. Using Direct Metal Laser Melting (DMLM) additive technology to make the new brackets has slashed scrap material waste by as much as 90%, reduced the part weight by 10%, and significantly reduced supply chain costs by manufacturing in-house.



CASE STUDY

GE9X Titanium Aluminide low pressure turbine blades

At its facility in Cameri, in northern Italy, Avio Aero – a subsidiary of GE Aviation – is additively manufacturing turbine blades used in the GE9X engine for Boeing’s next-generation 777X jets. These blades spin at 2,500 times per minute inside the engine and face searing heat and titanic forces.

Avio Aero’s modern factory houses a fleet of over 35 Arcam EBM A2X and Spectra H machines. Each A2X machine can simultaneously print six turbine blades using a powerful, 3-kilowatt electron beam in about three days. The new Arcam Spectra H machines can produce up to 10 blades in around the same amount of time.

The electron beam heats and melts titanium aluminide (TiAl) powder, layer by layer, to form the blades that are each 40 centimeters long.

60,000 blades
are made a year



LPT blades in the powder removal station

Additively manufactured TiAl blades are half the weight of traditional nickel alloy turbine blades used in aviation. For the GE9X engine, this means a fuel consumption reduction of 10% (as well as decreased emissions), compared to its predecessor, the GE90.

Collaboration again has been key to Avio Aero’s successful shift to serial production. A dedicated team of GE Additive technicians are embedded at the Cameri plant, working directly with Avio Aero’s team to support and service the EBM machines. An additional team of 10 people from Arcam, solely supporting Avio Aero, works closely with colleagues on-site in Italy.



Arcam EBM A2X



Arcam EBM Spectra H



Embracing change

These three, real-world case studies of serial additive production have also involved a significant learning curve for teams across GE, who along the way have absorbed valuable lessons in change management.

It’s important to view the path to serial additive production as a marathon, not a sprint. Mapping out a plan and the business case and detailing the reasons why additive manufacturing makes sense in your own situation, should be the first step when shaping your additive technology strategy.

Many users of metal additive technologies initially exhibit early exuberance and are excited to dive in.

However, production challenges — such as build stops, build failures, machine-to-machine variations, and build variations — can cause consternation and lead to a drop in your team’s

It’s important to view the path to serial additive production as a marathon, not a sprint.

enthusiasm. Before those issues are addressed and overcome, a phase called the “trough of disillusionment” might ensue.

However, once those hurdles are resolved and serial production starts to become a reality, leadership realizes and embraces the impact additive can bring across its business.

Addressing production challenges

Companies on the path to additive serial production typically encounter three primary production challenges:

1. PRINTING REPEATABILITY

This might include site-to-site or machine-to-machine variation or powder lot-to-lot variation, which doesn't come into play when you're making a single prototype using one process from a single powder lot on a single machine.

When addressing key factors contributing to variation, it is vital to identify the "critical Xs." These include machine-related factors such as "tool path" settings (power, speed, spacing) in your parameters, chamber environment (e.g. gas flow and oxygen), or mechanical alignment. Other critical Xs might relate to powder chemistry, powder handling and post-processing.

For matters such as power and gas flow, it is equally important to understand the ranges of control. What kind of variation can you withstand across the entire build plate? Issues also might occur when machines are not "locked down" in a production configuration, or when incomplete instructions are provided for operating and maintaining the machines.

Also, consider your preventive maintenance schedule. How often, for example, do you need to validate your machine calibration? How often do you need to recalibrate the oxygen level sensors or check the gas flow within the machine? How often do you need to change out your filters?

It is important to document, maintain and control all these factors.

2. PART QUALITY

To achieve consistent part quality, it is important to establish a solid quality plan that involves multiple departments, including engineering, manufacturing and quality.

Your quality organization needs to clearly understand what the design intent is, and how the manufacturing team is developing the part to meet that intent.

First, develop an overall control plan and establish an inspection plan and techniques for producing additive parts. The unusual and sometimes exotic



geometries made possible by additive might create new challenges for those charged with inspecting those parts. What techniques are best for this – white light, CMM, X-Ray, FPI or CT – to ensure design intent is achieved?

Part quality starts with powder — how you spec it from vendors and how you handle it. It is important to create and adhere to proper metal powder handling and storage procedures, while also exercising continuous process validation to ensure you have a stabilized process.

Those active only with conventional manufacturing may be unfamiliar with aspects of this. Powder can be reused and recycled, but it needs to be carefully documented and controlled -- and must adhere to appropriate environmental, health and safety procedures.

3. MANUFACTURING PRODUCTIVITY

To maximize productivity, one needs a thorough understanding of the primary factors that influence build-time trade-offs.

For example, going from a single-laser to a dual-

laser system does not necessarily translate into twice the speed or output. You need to consider your tool path and your re-coating time, while also ensuring you don't have laser-to-laser interaction.

To capture total manufacturing productivity, you also need to consider factors outside the machine.

Managers need to have the ability to adopt and scale up a "lean" shop as a fleet of additive machines. Consider how you can reduce the time needed to switch over between builds, how best to manage the post-processing functions, and how to develop your parameters. You need to take a holistic view of the entire process when attempting to boost productivity.

And, of course, from the outset, you must also optimize and design the build platform and part supports for commercial production. Consider if you can use traditional machines or automation to remove supports.

5 Considerations when transitioning to serial additive production

As you begin planning your additive industrialization strategy and a shift to serial production, consider the following points:

1. Build your design with production and process in mind

Understand that there are hundreds, if not thousands, of variables in the additive manufacturing process, and include everything from how your vendor creates the powder, to your quality inspection techniques.

2. Determine your vertical integration strategy and the impact it may have on productivity

Lead time and hardware final cost can be highly influenced by your overall business strategy. Key post-processing steps (HIP, VSR, support removal, final machining) should be researched to determine the best blend of in-sourcing vs. outsourcing.

3. Identify your “critical Xs” and their related tolerance ranges

The biggest hurdle we see in going from prototyping into production is in identifying and documenting which of your critical Xs are most important to your part, material and cost requirements.

4. Employ statistical quality control measures

You must determine how best to monitor and control those factors to ensure reliable consistency. Using statistical quality control measures will help to show that you have the repeatability required to satisfy the regulators in the demanding industries that you serve.

5. Develop knowledge transfer processes and do cross training across the various engineering disciplines

In our experience, we’ve come to understand the critical importance of collaboration and communication among all parts of the organization involved in this journey. Without co-locating our design, material, manufacturing, and quality engineers alongside one another during the part development process, the LEAP fuel tip might have taken several more years to complete.



Choosing the right partner

Choosing the right machine for serial production starts with understanding the requirements of your finished designed additive part and marrying that with the business plan.

As we have stated, additive manufacturing is like a marathon. And in this case, machine selection is like selecting running shoes. With the wrong pair of shoes, you can still finish the race, but it may be more painful and not the desired outcome you were looking for. One major pitfall is evaluating piece part cost based on parts per platform. We have found that loading a platform with as many parts as possible is not necessarily the most productive strategy.

Understanding trade-offs between different printing modalities will help determine which one is better suited to meet your requirements.

Concept Laser M2 Series 5

GE Additive spent countless hours working closely with GE Aviation on the latest iteration of the popular Concept Laser M2 system – the workhorse on our fleet of DMLM systems. The new Concept Laser M2 Series 5 meets customer expectations for high quality, repeatability, and usability.

The M2 Series 5 is a system that allows our customers to take full advantage of design for additive to achieve design performance targets, consistent material properties and productivity to enable business outcomes

Designed for maximum performance, the M2 Series 5 offers optimized system speed, uptime, productivity and reliability, part-to-part and machine-to-machine consistency, quality control, as well as process validation.

The M2 Series 5 is the optimal system for customers wanting to unlock the potential of volume additive production.

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- Improved part consistency build-to-build, and machine-to-machine based on machine architecture, calibration and control
- Higher productivity potential enabled by machine architecture (# of lasers, 3D optics, software, gas flow)
- Utilization and reliability (operating time + corrective maintenance downtime)
- Part yield
- Up to 20% finer feature resolution
- Unique safety system: glovebox system for non-contact handling of reactive materials, better filter change, inerted sieving and powder exchange





Concept Laser M Line

The M Line offers a new type of modular machine architecture with an unprecedented level of automation and innovation, allowing economical series production on an industrial scale.

The basic idea is to physically decouple the machine units used for part production and for set-up and dismantling processes. These tasks can now be carried out in parallel and physically separately from one another thanks to the modular architecture.

As a result, current stoppage times for the machines, stemming from manual processes

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such as supplying or exhausting metal powder, are reduced to a minimum. This will deliver considerable time and cost savings.

- Time-saving exposure coating strategy with supreme quality standards
- Redundancy of build plate cover thanks to the lasers
- Switchable filter units for maximum machine running time
- Completely redeveloped and modular software, designed for series production
- Unique innovative safety concept
- Automatic tool changeover without any interruption to part production (in development)

Arcam EBM Spectra H

Setting the pace is GE Additive's Arcam EBM Spectra H. With an extended build platform and capability to produce parts at temperatures exceeding 1,000°C, the machine's enhanced capacity opens new opportunities to produce high-integrity parts larger and faster than ever before.

As part of a system that simplifies operation and maximizes output, Spectra H is the evolution that's helping the industry take the next step forward. The newly designed and expanded build chamber, 39% larger than the previous generation machine, allows the Spectra H to deliver market-leading, high-temperature additive manufacturing.

Movable heat shields create improved insulation, forming the ideal environment for exceptional part production. An auto-calibrated, 6 kW beam provides a 100% increase in power to provide up to 50% faster builds, allowing manufacturers to begin transitioning into high-volume outputs. With this extended platform, it is possible to print larger parts than ever before and produce more parts at one time. And with Spectra H's high-heat capability, users can incorporate new alloys into production to expand their offerings, including high-temperature, crack-prone materials.

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- Largest EBM build volume for high-heat, crack-prone materials
- Auto-calibrated beam for precise part production
- Closed powder handling system for powder batch integrity for optimal part production
- Movable heat shields and improved temperature management
- Automated powder distribution and powder recovery station
- 100% increase in power for up to 50% faster builds
- Automated system for reduced operator dependency and optimal quality control





Arcam EBM Spectra L

Our latest innovation, the Arcam EBM Spectra L, offers increased productivity and reduces cost per part by 10%, from its predecessor the Arcam EBM Q20plus. Due to an increased beam power to 4.5kW and enhancements in the beam control, the build speed is increased by 20%.

The improved melt process results in consistent material properties for thin and bulky geometries. In addition, the Spectra L offers the largest build volume of our Arcam EBM machines, allowing enhanced capacity to produce high-integrity parts larger, and faster, than ever before.

- Increased productivity for reduced cost per part, thanks to increased build speed and the largest build volume
- Excellent part quality, consistent material properties for thin and bulky geometries
- Integrated system architecture, with standardized IoT interface, data analytics for machine health monitoring and our new Powder Recovery Station, PRS 30

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AP&C Powders

Certified to provide materials to highly regulated industries, such as aerospace and medical, AP&C offers high-quality premium powders that are produced in-house.

AP&C applies a unique Advanced Plasma Atomization (APA) technology, unmatched expertise in metal powders, and unparalleled testing and quality standards to everything we make.

We create powders that are highly spherical, with high processability, excellent flowability, and low porosity. We also create high performing powder equipment for every additive technology.

That means fewer defects, more efficient processing, superior quality, and a faster entry into additive manufacturing. Because when your products need to be flawless every time, your powder solution does, too.

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GE Additive's AddWorks™ Consulting Services

Moving from prototyping to serial production can be a big leap for any organization. GE Additive's AddWorks team can help make your journey easier. The team consists of design, materials and manufacturing engineers that help organizations navigate the challenges associated with the development, industrialization, and qualification of complex additive components and systems. AddWorks can bring this expertise to help you.

Working with GE Additive will help your organization:

- Accelerate the adoption of additive in your product portfolio
- Get your additive components and systems to serial production faster
- Reduce trial-and-error costs (and time)
- Bridge the additive talent gap while you are building your team

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GE Additive

Are you ready?

To turn a business case into a full-scale production.

To take metal additive further, faster.

To transform the way business is done.

To deliver innovation at the speed of today.

To look forward, not back.

When you're ready to turn complex into your competitive advantage, the pioneers in full metal additive production are ready to help.

Let's talk.

[ge.com/additive](https://www.ge.com/additive)