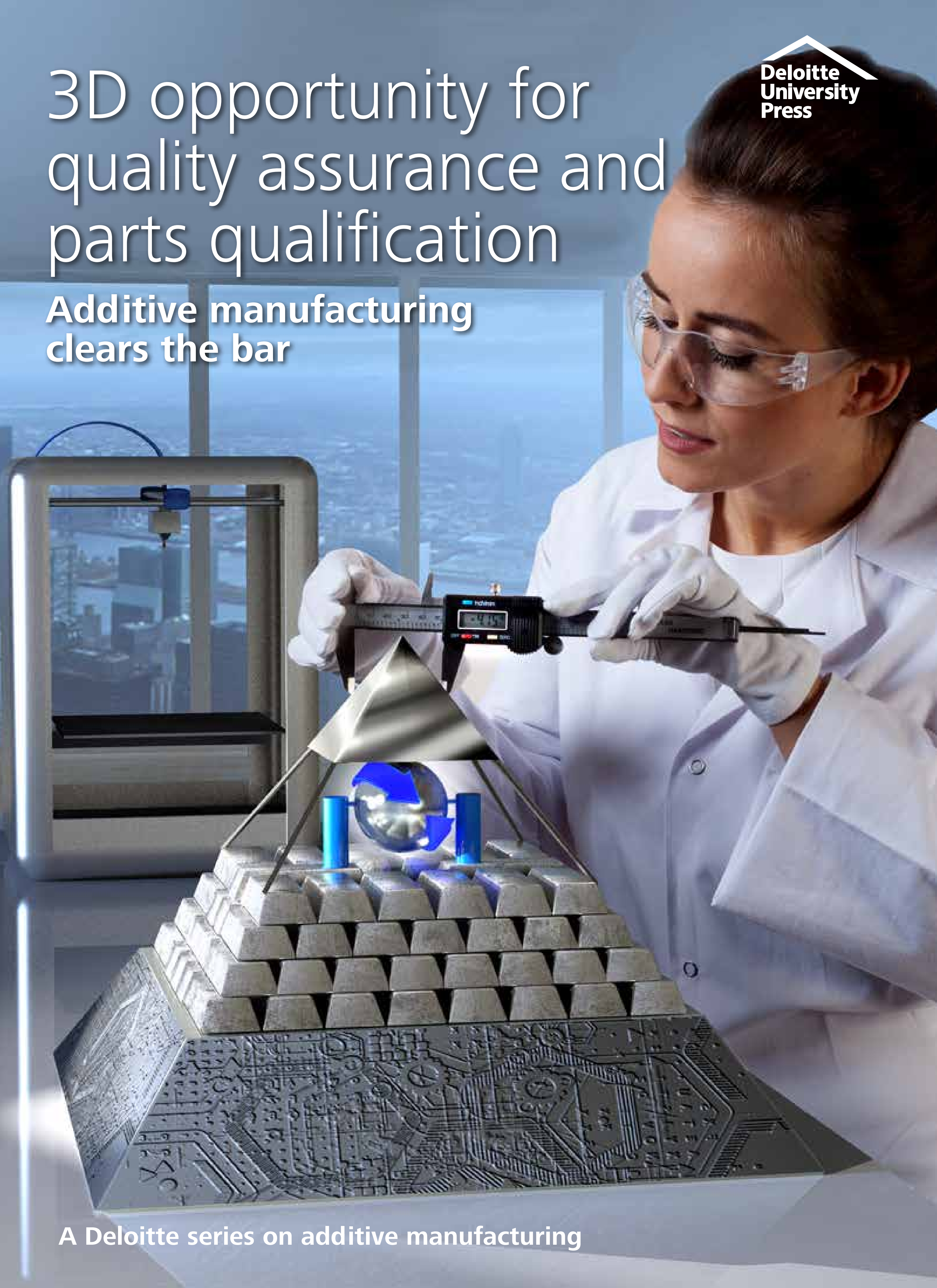
3D opportunity for quality assurance and parts qualification

Additive manufacturing clears the bar

Deloitte University Press



A Deloitte series on additive manufacturing

Deloitte Consulting LLP's Supply Chain and Manufacturing Operations practice helps companies understand and address opportunities to apply advanced manufacturing technologies to impact their businesses' performance, innovation, and growth. Our insights into additive manufacturing allow us to help organizations reassess their people, process, technology, and innovation strategies in light of this emerging set of technologies. Contact the authors for more information, or read more about our alliance with 3D Systems and our 3D Printing Discovery Center on www.deloitte.com.

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Introduction

> "One of the most serious hurdles to the broad adoption of additive manufacturing of metals is the qualification of additively manufactured parts.[1]"

ADDITIVE manufacturing (AM) produces objects by layering materials such as metals, composites, or polymers to produce a three-dimensional part rather than, for example, machining parts from blocks of raw material, as with conventional manufacturing. However, while companies have widely explored AM's potential to shrink the scale and scope necessary for manufacturing, bring to life previously impossible designs, and alter the makeup of organizational supply chains,[2] several significant hurdles prevent its wider adoption.

One of the most important barriers is the qualification of AM-produced parts.[3] So crucial is this issue, in fact, that many characterize quality assurance (QA) as the single biggest hurdle to widespread adoption of AM technology, particularly for metals.[4] Put simply, many manufacturers and end users have difficulty stating with certainty that parts or products produced via 3D printing—whether all on the same printer or across geographies—will be of consistent quality, strength, and reliability. Without this guarantee, many manufacturers will remain leery of AM technology, judging the risks of uncertain quality to be too costly a trade-off for any gains they might realize.[5]

QA presents a multifaceted challenge, encompassing both the scale and scope of production. Indeed, quality doesn't just exist on one dimension, and each area should be addressed for parts qualification—and AM's potential—to be more fully realized. Figure 1 summarizes the major facets.

Figure 1. Facets of AM quality

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In order to address the challenge of certifying quality for AM-produced parts along these four facets, manufacturers can develop capabilities that will enable them to:

- **Identify** the level of QA their products need, and what level of risk they are willing to assume

The roots of 3D printing go back nearly three decades. Its importance is derived from its ability to break existing performance trade-offs in two fundamental ways: First, AM reduces the capital required to achieve economies of scale; second, it increases flexibility and reduces the capital required to achieve scope.[6]

Capital versus scale: Considerations of minimum efficient scale can shape supply chains. AM has the potential to reduce the capital required to reach minimum efficient scale for production, thus lowering the manufacturing barriers to entry for a given location.

Capital versus scope: Economies of scope influence how and what products can be made. The flexibility of 3D printing facilitates an increase in the variety of products that a unit of capital can produce, reducing the costs associated with production changeovers and customization and, thus, the overall amount of required capital.

Changing the capital-versus-scale relationship has the potential to change how supply chains are configured, and changing the capital-versus-scope relationship has the potential to change product designs. These impacts present companies with choices on how to deploy AM across their businesses.

Companies pursuing AM capabilities choose between divergent paths (figure 2):

Path I: Companies do not seek radical alterations in either supply chains or products, but they may explore AM technologies to improve value delivery for current products within existing supply chains.

Path II: Companies take advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the products they offer.

Path III: Companies take advantage of the scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer.

Path IV: Companies alter both supply chains and products in pursuit of new business models.

Figure 2. Framework for understanding AM paths and value

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- **Accurately predict** whether parts will meet specifications when built under "idealized" conditions
- **Ensure repeatability, consistency, and reliability** across different AM machines and geographies
- **Incorporate the appropriate technologies and capabilities** necessary to qualify AM-produced parts, based on the target QA level

Based on a review of the technical literature, we have developed the AM Quality Pyramid to provide an organizational schema through which to approach QA for additively manufactured parts and to describe approaches for accurately predicting quality pre-build, promoting repeatability, and incorporating the technologies necessary for QA.

In doing so, we argue that not all AM-produced end-use parts will require the same level of QA. Thus, the same robust approach may not be suitable for all organizations. To help manufacturers consider the appropriate QA level, we illustrate a continuum of options, with simple inspection on one extreme and the complete pyramid on the other. By identifying their position along this spectrum, manufacturers can begin to understand the level of QA their products require and, thus, recognize which strategies to use to qualify AM-produced parts.

Historically, most firms exploring AM technology fall into path I, using it largely for rapid prototyping and iterative design for parts meant to be manufactured via AM.[7] As additive technologies advance, opportunities for their use will continue to grow and may eventually prompt a strategic shift to paths II, III, or IV. A needs-based quality management approach is essential to any such shift, as the ability to qualify and certify parts remains essential to moving to wider use of AM.

Toward a solution

The AM Quality Pyramid

TODAY, firms seeking to qualify AM-produced parts generally apply the same processes used for parts produced by traditional methods: namely, extensive non-destructive and destructive testing of hundreds of copies of the final part.[8] This is expensive for any type of production; it also negates many of AM's identified economic and operational advantages, which include low-volume or one-off printing.[9] Thus, the prospect of printing hundreds of parts, one by one, solely for testing can be daunting.

Still, some firms find AM's demonstrated benefits so compelling that they pursue this process anyway, a testament to the value of 3D printing in many instances.[10] To make this leap on a wider scale, however, most organizations require a more sustainable, feasible approach to qualifying and certifying parts.

Thus, a different methodology—one taking AM processes into account—may offer greater benefits. Indeed, unlocking the full potential of AM may necessitate a reversal of the qualification process to which engineers are accustomed: the development of a means to certify AM parts based on design, as well as observations and corrections made during the build process, rather than verifying performance *after* fabrication.

Unlocking the full potential of AM may necessitate a reversal of the qualification process to which engineers are accustomed.

To address the differences between AM and conventional processes, the science and engineering community is gravitating toward an AM solution centered on three pillars: QA derived from build planning and build monitoring/inspection, linked together with feedback control, described in table 1.[11] Later in this paper, we discuss in detail some of the "intelligent" machine control methods in development meant to preemptively adjust build parameters to avoid situations that increase the risk of defects.

In addition, several supporting factors underpin build planning, build monitoring, and feedback control—and, by extension, effective QA schemas. These include enabling factors such as standards to guide the process,

Table 1. Key elements of quality assurance in AM

AM pillar	Description
Build planning	The use of advanced modeling and simulation to develop a plan for a machine to produce a specific part
Build monitoring	Monitoring with sensors the build process as the part is being constructed
Feedback control	Using data from the build monitoring sensors to iteratively update the build planning process in real time

calibration, raw materials, and a build data "body of knowledge" that enables manufacturers to catalog and leverage past experiences. Deloitte has developed the AM Quality Pyramid to capture these key elements of AM QA and map the ways in which they interrelate and build upon each other (figure 3).

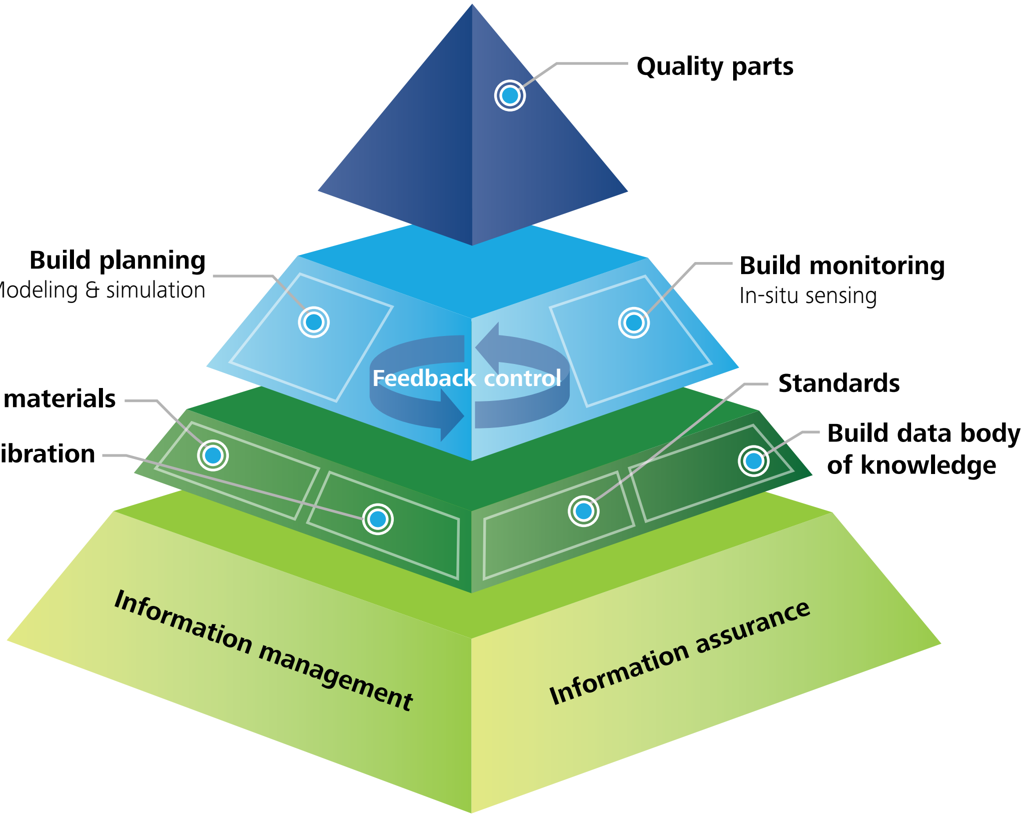
The ultimate goal—quality parts—rests at the apex. Directly supporting this goal are the key components necessary for successful QA: build planning and build monitoring, linked by feedback control. Supporting these processes is the third tier, consisting of the enabling factors. Finally, at the base rest information management and information assurance, which underpin the entire QA process; without reliable, accurate data about the design or process, the pyramid cannot remain structurally sound.

In this section, we explore current research at each level of the pyramid, moving from top-down to illuminate various considerations and approaches relevant to each, along with illustrative examples of ongoing real-world applications.

It is important to note that this paper does not attempt an exhaustive review of research literature related to the topic of parts qualification or QA for additive manufacturing.

> As manufacturers seek to qualify parts, they must first understand and articulate what they are striving for.

Figure 3. The AM Quality Pyramid



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Rather, the intent is to provide a few illustrative examples of research in each area; several more detailed reviews are available on this topic.[12]

Starting at the top: Defining "quality"

The most important questions of all must be addressed at the outset of any QA development: What does "quality" look like, and how is it defined in relation to this particular AM process? Without an understanding of what constitutes quality in each particular case, it will be difficult, if not impossible, to develop a consistent approach to achieving it.

At the same time, however, quality will not—and should not—look the same for every type of part and product. Quality exists on a spectrum and is often contingent on the intended use of the part; a 3D printed action figure is held to a different type of quality control than a component on a fighter jet. In the former case, a difference of a few microns in the geometry of the final part makes little difference; in the latter, it could be a matter of life and death. As manufacturers seek to qualify parts, they must first understand and articulate what they are striving for.

Furthermore, part quality is more than just the shape of the finished part. Fundamentally, quality is about a part's ability to perform the task for which it was designed, while maintaining structural integrity. Contributing factors are usually included in a part's specifications and typically include geometry, surface finish, and material properties (table 2).[13]

Each of these factors depends directly on build process parameters, including raw materials.[14] Thus, controlling and assuring the build process—and, by extension, ensuring uniformity among these three criteria—figure strongly in the overall quality of a finished part.

Build planning: Increasing complexity, growing data requirements

In most AM applications, a three-dimensional shape is digitally sliced into thin layers, and a tool path[15] is defined for each slice to create the part layer by layer.[16] Traditionally, part geometry has dominated tool path planning, but achieving quality control in AM involves greater command over parameters beyond geometry. These parameters can include laser power, laser scan speed, and build chamber temperature, to name a few. Each of these factors contributes to the outcome of a build, and aberrations in any could impact final part quality.

Advanced computational models, which can simulate the physical phenomena associated with AM processes, are useful build-planning tools. Computational models can predict how a part will behave in response to environmental stresses. Consider the example of a passenger jet with engines mounted beneath the wings: Engineers can use simulation to estimate the mechanical stress that the pull of

Table 2. Dimensions of quality

Quality dimension	Definition
Geometry	The shape of the finished part and how it will fit with other parts
Surface finish	The desired smoothness, roughness, or other functional surface treatment of the finished part
Material properties	A variety of attributes, including mechanical strength, stiffness, and fatigue life

the engines will cause on the wings, without conducting a physical experiment (figure 4).

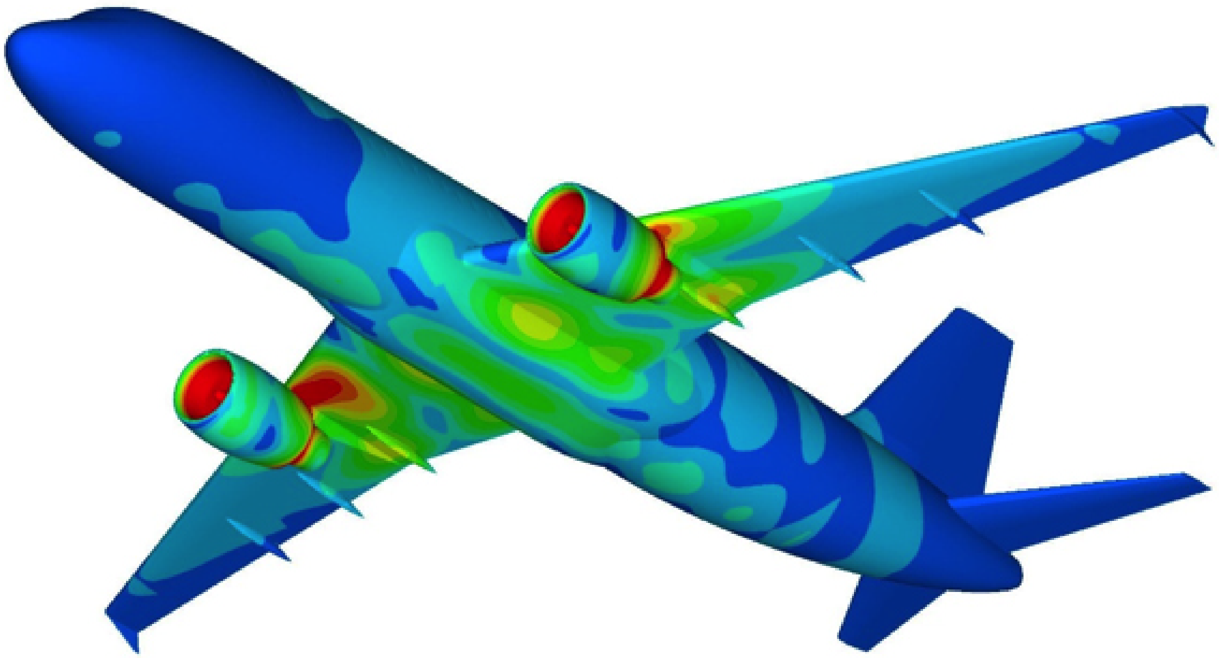
For AM build planning, engineers seek to extend this computational approach to solving the multiphysics process of AM, which includes the mechanics of the part being built, the surface tension of the liquefied metal in the build area, and the way that heat from, for example, a laser is applied and dissipated.[18]

And these data points represent merely the tip of the iceberg. Researchers cite more than 130 variables for which designers may need to account in a fully representative simulation, including a wide range of time and length scales.[19] These phenomena are complex enough to simulate individually; creating a concurrent model that builds in multiple factors can make the process even more challenging.[20] As with the 3D printing process itself, every additional factor adds another layer of modeling complexity. Yet this process represents a foundational area: Accurate simulations are essential for developing build plans that adjust input parameters dynamically to avoid defects and, ultimately, guarantee quality.

Due to these simulations' complexity and scale, most computational models are run in high-performance computing facilities, as the wide range of data requirements increases computational load to the point where it approaches current limits of high-performance computing technology.[21] Currently, some of the most sophisticated models of AM processes are found at the US National Laboratories, which possess massive computing capabilities.[22]

Thus, availability of specialized computing resources becomes a potential limiting factor for QA, as most companies lack ready access to this level of computing power. Fortunately, approaches to clearing this barrier may be materializing: Computing power continues to grow, and some commercially available simulation and software solutions specifically geared toward AM in a production environment,

Figure 4. Results of a numerical simulation showing peak stresses on a passenger aircraft in flight, with stress concentrations near the engine mounts, a result of the engines pushing the plane forward.[17]



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such as 3DSIM's EXASIM, are emerging.[23] The TRUCHAS code, originally developed by Los Alamos National Laboratory to model the casting processes for nuclear fuel rods, provides a trenchant example. TRUCHAS simulates many of the important parameters for modeling the AM process: solid mechanics, multiple types of heat transfer, and the changeover between solid and liquid phases for a metal.[24] It is available via open source to anyone with the computing power to use it.

Aside from computing and data management capabilities, engineers must also consider modeling software and the code that enables calculations. Approaches include open-source code,[25] commercial software,[26] and proprietary tools developed in-house—dependent on individual organizational needs.[27]

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Proliferation of computing power has helped lower barriers to entry for complex modeling and may even be setting the stage for in-the-loop computing on the production floor. Given the enormous computing power requirements, it remains a challenge to use existing models in a production environment, although these requirements may become more realistic as computing power increases and more solutions enter the marketplace. A recent National Academies of Sciences Predictive Theoretical & Computational Approaches for Additive Manufacturing Workshop prioritized the development of "reduced order models,"[28] which focus on dramatically reducing the computational intensity of simulations by making assumptions to constrain them, and by leveraging already-existing libraries of similar, catalogued features.[29]

Build monitoring: Measuring the build process in real time

During the parts qualification process, AM build monitoring systems must document the build process to ensure specifications are met.[36] Several key sensing modalities can be used to measure relevant parameters, all of which are within reach with today's technology (table 3).

Table 3. Examples of measurement modalities

Sensing modality	Function
Accelerometers	Measure vibration of the print head during fused deposition modeling and detect potential anomalies[37]
Ultrasound sensors	Ensure the final part is free of internal voids, an important capability since voids create stress concentrations that can lead to premature part failure[38]
High-resolution photography	Allows for near real-time inspection of parts in the build chamber[39]
Thermal imaging	Monitors size, shape, and relative temperature distribution of the melt pool[40]
Pyrometry (photodiode)	Measures light intensity at a single point and correlates to temperature[41]

ADDRESSING COMPUTING AND DATA CHALLENGES

The physical challenges of guaranteeing quality for AM are substantial and widely accepted. However, equally important—and less often discussed—is the issue of data management. Both build planning and build monitoring add enough data to challenge today's most advanced high-performance computers. The data requirements are, quite simply, staggering.

For example, the Accelerated Certification of Additively Manufactured Metals Initiative at Lawrence Livermore National Laboratory runs some of the most sophisticated models of the powder-bed fusion AM processes available today.[30] In simulating the builds of relatively small and simple parts at only moderate resolutions, their supercomputer runs routinely produce outputs of hundreds of gigabytes of data, spread over hundreds of thousands of files.[31] While the current volume of data is not that challenging, as part volume and simulation resolution both grow, data requirements will increase by orders of magnitude in the near future.

Video data from process monitoring drives even larger requirements. Berumen et al. describe a technique for monitoring the build process with full-frame video.[32] To simultaneously capture the full chamber and provide sufficient detail to resolve the melt pool at a frame rate fast enough to keep up with the motion of the laser results in 1.5 petabytes (1500 TB) of data for the same six-hour build. This volume of data is roughly the equivalent of more than 57 years of high-definition streaming video.[33]

Scientists and engineers are innovating in both these areas to reduce data requirements. Leaders in the field of computational modeling for AM describe "reduced order models" which bound the problem and allow various shortcuts.[34] Berumen et al. describe a creative solution to the data challenge around video monitoring: use of mirrors to image down the axis of the laser beam, providing a "tracking view" of the melt pool and dramatically reducing the data requirements.[35] Although the resulting video data is considerably smaller, this approach still results in a 12.7 TB file for a six-hour build. In some cases, engineers will need to perform this process—with its attendant data requirements—for every part. Further adding to data load, organizations may need to maintain that data for a prescribed amount of time post-build, and be able to access and analyze it on demand.

In the future, a combination of data reduction techniques such as these, paired with steadily increasing computing power, will help open the door for real-time processing and feedback control.

Together or separately, these technologies can measure multiple aspects of a build. Of principal interest for powder bed-based AM technologies, for example, is the size and temperature of the melt pool, which has been demonstrated to drive microstructure, material properties, surface finish, and overall part performance.[42] Measuring the melt pool in near real time can be accomplished with the combination of a calibrated digital infrared camera and a photodiode sensor to measure the intensity of light.

Such a technique is described in a 2010 joint publication from CONCEPT Laser and Katholieke Universiteit (KU) Leuven in Belgium. This study imaged the melting/resolidification process with high-speed video and a photodiode to estimate melt pool temperature and size over time, and proposes a capability to use sensor information to document the build process for applications with stringent quality requirements.[43]

It is important to note the criticality of sensor calibration for this type of measurement. Many factors govern the resolidification process; put very simply, metals subjected to different melt temperatures during the build process will have different strength levels, which could ultimately impact function and quality.[44] To this end, another study from the University of Texas's Keck Center for 3D Innovation described development of a technique that complements the CONCEPT Laser/KU Leuven work: a physics-based method for calibrating infrared cameras to ensure accurate temperature measurements. The research highlights the importance of proper camera calibration in providing accurate monitoring during the build process, and argues that precise temperature readings are essential.[45]

Melt pool monitoring data alone is valuable. Measuring these parameters can be used alongside other models to verify microstructure and ultimately guarantee part specifications or, conversely, to identify defects as they occur and stop the build process early. However, a more effective application of such data would be to adjust input parameters in real time when sensors detect non-ideal conditions—a process known as feedback control.

Maintaining control over build processes enables manufacturers to achieve the consistent geometries, surface finishes, and material properties that underpin quality.

Feedback control: Linking build planning and build monitoring

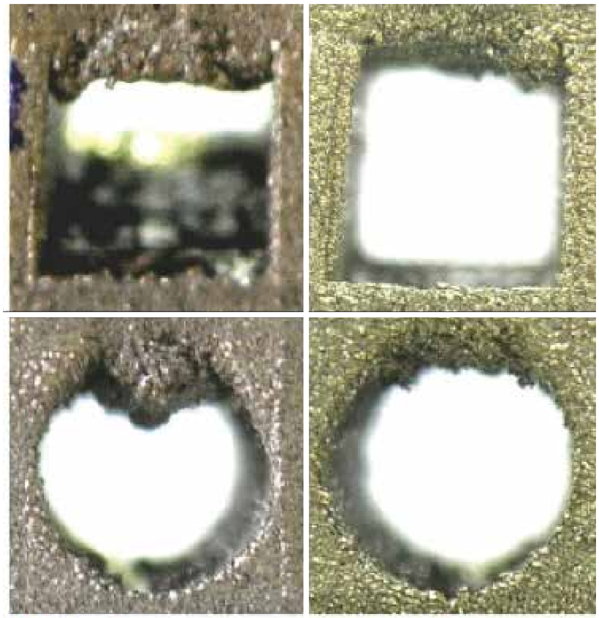
It's often not enough to detect anomalies. Ideally, systems should be able to take action to correct them. Feedback control refers to the ability to detect build-plan deviations and automatically adjust systems to correct for them. Applying this capability to AM build planning and build monitoring is crucial to achieving QA. Maintaining control over build processes enables manufacturers to achieve the consistent geometries, surface finishes, and material properties that underpin quality.

Emerging examples of feedback control can illustrate its impact: In one case, researchers at the University of Texas designed a system to modulate laser power and scan rate[46] based on the temperature and size of the melt pool, adjusting power accordingly when these attributes changed.[47] In a related effort, a team at Pennsylvania State University developed a system to measure temperature at the start of each layer. In the event that the temperature exceeded a predetermined threshold at the planned start location, an algorithm adjusted the process to start building at a lower temperature location.[48] And at least one commercially available AM system already offers feedback control, using a thermal camera to measure laser power and scan rate in response to size, shape, and temperature of the melt pool.[49] Additionally, we believe several major aerospace and defense firms are finding success in this area as well.

An illustrative example of feedback control also comes from the KU Leuven group, which demonstrated the effect of simple feedback control based on the temperature of the melt pool, applied to a challenging build: closed overhangs.[50] The results show a dramatic increase in the surface integrity of the overhangs.[51] (See figure 5.)

As AM technology continues to develop, feedback controls should be tightly integrated with multiphysics simulations used in build planning. Instead of simply controlling conditions to keep the melt pool at a constant size and temperature, sensing systems will report actual readings back to the simulation, which can then recalculate and prescribe an updated build pattern in order to meet the desired specifications.

Figure 5. Experimental results demonstrating the effect of feedback control on a closed overhang with a length or diameter of 5MM—a particularly challenging AM application.[52]



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Supporting factors: Underpinning the AM Quality Pyramid

Supporting build planning and build monitoring are multiple factors, including standards, engineering and management controls, and a build data body of knowledge. At the base of the AM Quality Pyramid, information management and information assurance underpin and reinforce the structure.

Standards

Maintaining controls over the size, shape, and chemical composition of powders used in AM processes helps ensure consistent results, and standards are emerging to control these factors.[53] Standards are also available for destructive and non-destructive evaluation of finished AM parts.[54]

Despite these developments, as of October 2015 there are no broadly recognized, published standards for the *production* of AM parts. The area is, however, evolving rapidly. The American Society for Testing and Materials has designated a committee to define and issue standards for test methods, design, materials, processes, environment, health and safety, terminology, and potentially file formats.[55] Ideally, these standards will be applicable in the near future across multiple machines and processes, to help maintain consistency in a variety of situations.[56] Working with those who understand this evolving space can help manufacturers get a handle on newly accepted standards and assess how to incorporate them into existing AM approaches—or develop wholly new approaches instead.

Calibration, maintenance, and raw material quality and handling

Adopters must develop detailed maintenance and calibration plans for equipment, as well as define guidelines for raw material quality and handling. This represents an important competitive advantage; companies performing well in this area may hold their practices close to the vest. Production managers should carefully consider these factors as they develop and apply engineering and management controls across the AM production environment, perhaps incorporating skills and processes they may already have in place around process design and documentation and error minimization, such as Six Sigma.

Working with those who understand this evolving space can help manufacturers get a handle on newly accepted standards.

Build data body of knowledge

The "build data body of knowledge" refers to sharing detailed information about a variety of build situations. In this way, all can learn from collective experiences, advancing QA capabilities as a whole.[57] Should one team observe a process defect, sharing technical information about that feature, process, and result via a searchable database can help others avoid the same mistakes. Organizations such as America Makes, the US-based National Additive Manufacturing Innovation Institute, and the EU-based Standardization in AM are using collective knowledge to help drive standardization.[58]

Information management and information assurance

At the base of the AM Quality Pyramid, information management and information assurance enable the management of design/build information and its protection from unauthorized access or tampering.[59] The advancement and proliferation of AM technology is expected to drive considerable data requirements, increasing data generation by orders of magnitude, as this process will need to be repeated for every part and the data must be accessible for analysis on demand. Likewise, the data will need to be transmitted and secured both in advance, to help prevent hacking designs and, afterward, to help prevent corruption and/or loss. A manufacturer's ability to store, manage, and protect this information is likely to become an important differentiator.

Addressing the business challenges of quality assurance

THE AM Quality Pyramid offers a complete vision for QA in AM: a point where, through constant and robust monitoring, objects can be printed and certified, at a level of dependability and quality comparable to that of conventional manufacturing. Over time, as AM technology continues to develop and proliferate, many manufacturers will find that a robust QA schema similar to that of the pyramid is likely the approach best suited to their AM production needs.

However, not all manufacturers have need for the same level of consistency, and not all parts warrant the same vigorous level of QA. In these cases, a more modest QA scheme may be appropriate—as well as more cost-effective. As such, organizations should choose what level of QA is necessary for each part to help determine the most fitting approach.

A spectrum of capabilities

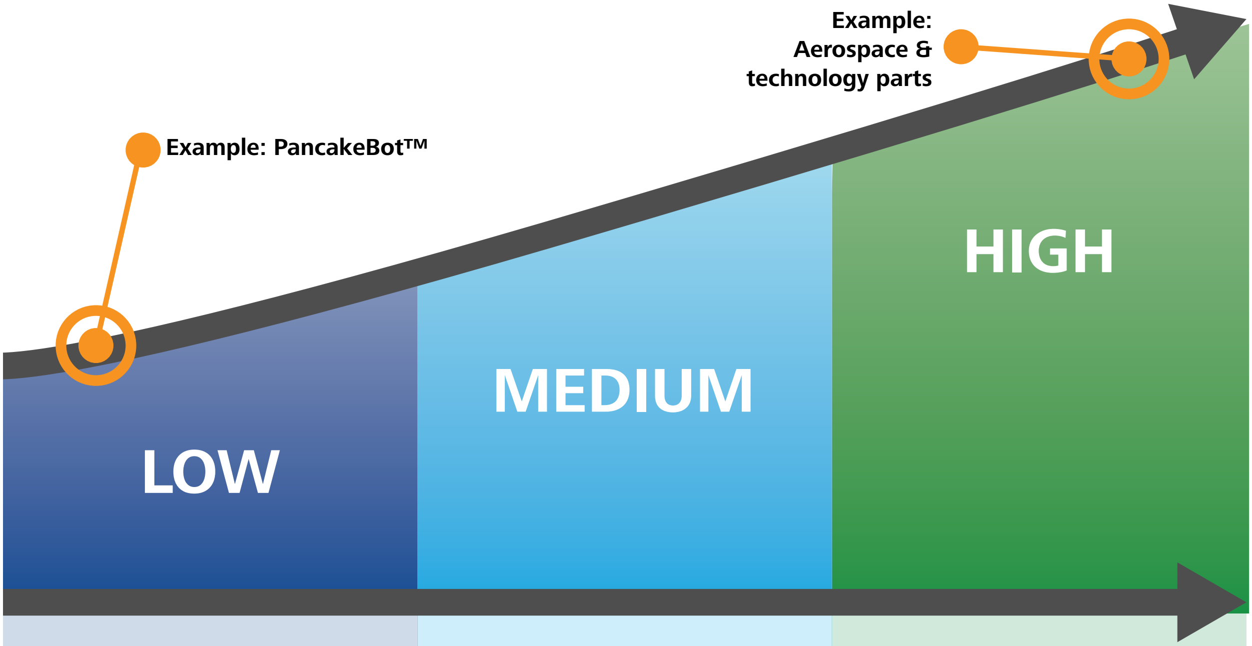
On one end of the spectrum, some applications may require little to no QA. Consider the forthcoming PancakeBot, a relatively simple 3D printer that extrudes pancake batter onto a hot skillet to create edible shapes.[60] Even for the most exacting engineer, "close enough" for a dinosaur-shaped pancake may be enough to pass muster.

Aerospace and defense firms, on the other hand, land on the much more stringent end of the QA continuum. The tolerance limit for aerospace manufacturers is typically less than 10 microns.[61] Failure here could mean more than just a disappointing breakfast—it might well be catastrophic. Thus, A&D will likely need to move toward rigorous, feedback control-based system over the next several years; indeed, the sector is already relatively more advanced than others in this area.

The majority of parts and products will likely fall between these two extremes, and manufacturers here have a more complex choice to make. They should first ascertain where on the spectrum they fall by developing a deep understanding of the requirements underpinning the need for QA, then develop a means to achieve it in a cost-effective way. Figure 6 depicts Deloitte's view of the various QA approaches based on the level of quality required for the end product.

They should first ascertain where on the spectrum they fall by developing a deep understanding of the requirements underpinning the need for QA, then develop a means to achieve it in a cost-effective way.

Figure 6. AM quality assurance continuum



Principal QA tool and description		
Manual inspection: Visual or manual measurement of finished parts and comparison against specifications **Mechanical testing**: Testing of parts under laboratory loading conditions to design load (non-destructive) or to failure (destructive) **Result**: Individual parts pass/fail	**Auditable process control**: Rigorous testing of a part printed under known conditions, quantification/codification of those conditions, and traceable, auditable reproduction of those conditions or other printers **Result**: All parts pass as long as desired conditions are maintained	**QAAM pyramid**: Advanced modeling, sensing, and feedback control work together to guarantee the quality of any part, on any machine with the capability to print it **Result**: Guaranteed quality for almost any part, or rejection of build plan up front if it cannot be built
Business enablers		
Investment in existing test and inspection technology Training of workforce in traditional T&E methods Low QA requirements or non-critical application	Creation of auditable manufacturing process, enabled by manufacturing IT Robust protocols to manage calibration Integration of sensing technologies to verify compliance Information assurance becomes important	Significant investment in R&D to develop modeling, sensing, and feedback control capabilities Marriage of high-performing computing with manufacturing Supported by enablers (see pyramid) Information management (10s–100s of TB) and information assurance are critical
Business outcomes		
Path 1: Can continue to produce tooling, fixtures, and limited production parts **Path III**: Can qualify novel products, but cannot assure quality at scale or scope	**Path II:** Can apply audit in remote locations to guarantee quality and allow supply chain evolution	**Paths II, II, IV**: Ability to produce almost any part and guarantee quality allows fundamental changes to the business model, both in terms of product and supply chain

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Low QA requirements: Taking a conventional manufacturing approach to QA

In an environment with minimal or low QA requirements—such as, again, custom-shaped pancakes—a simple "eyeball" check might be enough to declare that a product has met standards. In situations with slightly more demanding requirements, engineers may require measurements or mechanical testing—a simulation of loading conditions in a laboratory—to verify performance.

Inspection technology like this is widely available today and is already regularly used in a variety of industries. Implementation may thus prove a lower barrier, provided that manufacturers invest in both training and equipping their workforce, and that customers will tolerate the result. Additionally, due to its relative ease of implementation, this can prove a useful interim approach for manufacturers as they develop more a robust, long-term QA approach.

Organizations focusing on the least stringent quality levels may find themselves limited in their applications of AM. This sort of approach may be best suited for manufacturers within path I, using 3D printing for tooling, rapid prototyping, and other indirect applications. Some firms can also consider adopting low QA requirements within path III (developing and certifying new products with a high tolerance for variability) or within path II (building stopgap measures for keeping damaged equipment running while awaiting more permanent repairs). However, it is important to consider that manufacturers at this level may find it difficult to achieve scale by performing exhaustive inspection and testing of every part. Furthermore, firms operating at this level of QA may not realize more extensive supply chain benefits of AM, as they will be unable to certify any parts manufactured under different conditions.

> In fact, detailed process control of production operations is already fairly common for quality programs; adding AM represents a new layer on what is, for many, a well-established practice.

Medium QA requirements: An audit-based approach

Organizations with the need for stricter QA considerations that still fall short of full implementation of the highly technical elements of the AM Quality Pyramid can consider taking some conventional approaches to developing and testing a part. They can then codify the results of those tests into a "recipe": a detailed build procedure and prescription of build conditions that, through experience, have been shown to produce a part that passes inspection. During the actual build process, audit techniques can be applied to document that "recipe" conditions are met, regardless of where the part is built. This level of QA implementation relies on the creation of an auditable manufacturing process, and could require detailed calibration management procedures and integration of sensing technologies. Adopting an audit-based QA solution, and applying that audit capability in remote locations to guarantee quality, can enable firms to more fully leverage path II, supply chain evolution.

Many manufacturers may be well positioned to adopt this level of QA relatively rapidly. Leading aerospace and defense firms already apply tightly controlled and documented processes to ensure quality on flight-critical parts.[62] In fact, detailed process control of production operations is already fairly common for quality programs; adding AM represents a new layer on what is, for many, a well-established practice.[63]

> Guaranteeing quality on any part anywhere also unlocks both dimensions of demonstrated AM value: product evolution and supply chain evolution.

At this level, manufacturers may begin to see an exponential increase in data requirements due to the level of monitoring and the potential inclusion of supply chain partners in the QA process. (See sidebar "Addressing computing and data challenges.") Thus, information management and assurance—the bottom level of the Quality Pyramid—grow in importance. Indeed, firms should make sure they have information management strategies and capabilities in place that will allow for data collection, storage, protection, and analysis.

High QA requirements: Scaling the AM Quality Pyramid

Manufacturers with the strictest QA requirements, such as those in the aerospace and medical device sectors, may require a full application of the AM Quality Pyramid: advanced build planning and monitoring capabilities, linked together with feedback control. This can help certify the quality of any part, on any machine with the capability to print it, in any location.

Internal investment in R&D will likely be essential to developing high-level QA capabilities; due to the competitive advantage it typically creates, early leaders may be tight-lipped about their techniques. To address the supporting factors described in the AM Quality Pyramid, manufacturers may need to integrate high-performance computing and manufacturing. Information management also becomes critical, as single builds can result in 10s to 100s of terabytes of data. While initial investments may be high, however, they can pay strong dividends. The ability to fully certify AM-manufactured parts, and thus reliably print them on demand, anywhere, will likely be a significant competitive advantage.

Guaranteeing quality on any part anywhere also unlocks both dimensions of demonstrated AM value: product evolution and supply chain evolution. In this way, manufacturers can explore path IV: evolving supply chain with distributed manufacturing, developing advanced new products previously impossible to create through conventional methods, and potentially creating new operating models.

Raising the bar

As additive manufacturing continues to advance and moves beyond rapid prototyping into development of truly innovative parts and more efficient supply chains, it is important for manufacturers looking to take fuller advantage of AM's potential to find a way to ensure the parts they produce can be of consistent and reliable quality. To do so effectively, manufacturers should consider the following actions:

Evaluate the level of QA needed for each part. Not all parts or products will need the same level of scrutiny. Even within a single end product, manufacturers may find that one part—such as a hinge or bracket—can be held to a lower QA standard, while others, such as engine parts for the same aircraft, will need to pass the most stringent specifications. Assessing the level of QA actually needed can help ensure that manufacturers do not underprepare—and also that they do not over-invest in QA technologies that they may not need.

Consider adhering to lower standards on the AM QA continuum in the interim while developing capabilities to enable a more stringent QA process in the long term. Rome wasn't built in a day. Planning, building, and implementing a full QA process such as the AM Quality Pyramid takes time, training, and investment in new technologies, processes, and talent. Manufacturers can consider using approaches that fall lower on the QA continuum as a stopgap measure while developing more in-depth strategies. This may also ease the implementation process internally, as it gives an organization time to gradually incorporate and acclimate to new processes over time.

Take a full view of the production process. With AM, it will be important to understand status not only during the build but well beforehand, via simulations and modeling. This can enable manufacturers to avoid the often costly and inefficient process of having to test copies of a part post-production, an approach ill suited to AM. Given the current state and availability of high-performance computing required for this sort of approach, it will be crucial to consider what plans—or partnerships—should be in place in order to make progress.

Understand the data management challenges that may lie ahead. QA can require strong data management and access to high-performance computing. It will be important to determine what can be accomplished internally and whom to partner with to develop these skills.

When developing a plan for developing QA capabilities, assess not only where you are but where you wish to be. Manufacturers residing in path I whose long-term strategy involves supply chain evolution may wish to concentrate on QA approaches that enable the ability to print across wide geographical distances. Conversely, those whose long-term strategy focuses more on leveraging AM to manufacture entirely new products may instead focus initial QA efforts on other technologies. Taking a strategic approach to growth helps develop a QA process that enables and supports business goals.

As manufacturers look to adopt AM, creating a clear map to assuring consistent quality will remain a significant challenge. A systematic approach to quality assurance can help additive manufacturing continue to reach its potential.

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