Roland Berger Focus

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Advancements in metal 3D printing
Beyond powder bed – Additive manufacturing on the brink of industrialization

Roland Berger

Metal additive manufacturing is reaching the industrialization stage. While established additive manufacturing technologies are starting to come up against technology-inherent cost boundaries, new additive production concepts are shaking up the market. Companies must stay on top of the latest developments and actively include them in the creation and maintenance of their technology roadmaps. A structured approach that encompasses the entire solution space of additive manufacturing is therefore needed.

NEW OPPORTUNITIES ADD COMPLEXITY

The market for metal 3D printing or additive manufacturing is in motion, and manufacturing companies need to react. Additive manufacturing (AM), previously an expensive niche technology to create prototypes, is on the brink of becoming affordable for certain mass-production applications.

This breakthrough is the result not just of advances in the area of powder bed fusion by laser (PBF-L), a technology that is already well established for metal applications, but also growth in alternative additive technologies. Examples of such technologies include direct energy deposition, binder jetting, material jetting and material extrusion. These newer technologies are stirring up the market and are widely expected to drive down the cost of AM. They are also increasing the penetration of AM as industrial applications are no longer limited to the production of highly sophisticated parts such as gas turbine burners, satellite motors and custom prosthetics. The range of areas that can benefit from AM's unique capabilities – above all freedom of design and economical production of small lot sizes – is expanding all the time.

But there's a problem. From our project experience we know that many companies struggle to exploit the new potential offered by AM. Too many of them are taking a "wait and see" approach. The companies that are more active are generally focusing solely on PBF-L, powder bed fusion by electron beam (PBF-EB) and occasionally direct energy deposition (DED). Even they are neglecting the need for a well-crafted integrated production technology strategy with a time horizon of three to five years or beyond.

Why are so many in the industry holding back? The answer is not hard to find. Yes, the new technologies offer fresh opportunities, but they also make things a lot more confusing. As new firms enter the market with the latest technology, it becomes harder and harder for industrial players to stay up-to-date – and to separate the sometimes overenthusiastic marketing claims from the true capabilities of the new technology.

So, what should companies be doing about it? We believe that all players need to get a hold on what is going on in the market and develop an appropriate strategy. Below, we examine the PBF-L technology in detail, looking at how it performs with regard to part performance, lot size and costs, and how this may change in the future. We then turn to the alternative technologies, offering an overview of what they can do and how they perform for the same measures. Finally, to help hesitating companies get going, we suggest a four-step process that they can use to develop a comprehensive roadmap as a basis for their future technology strategy.

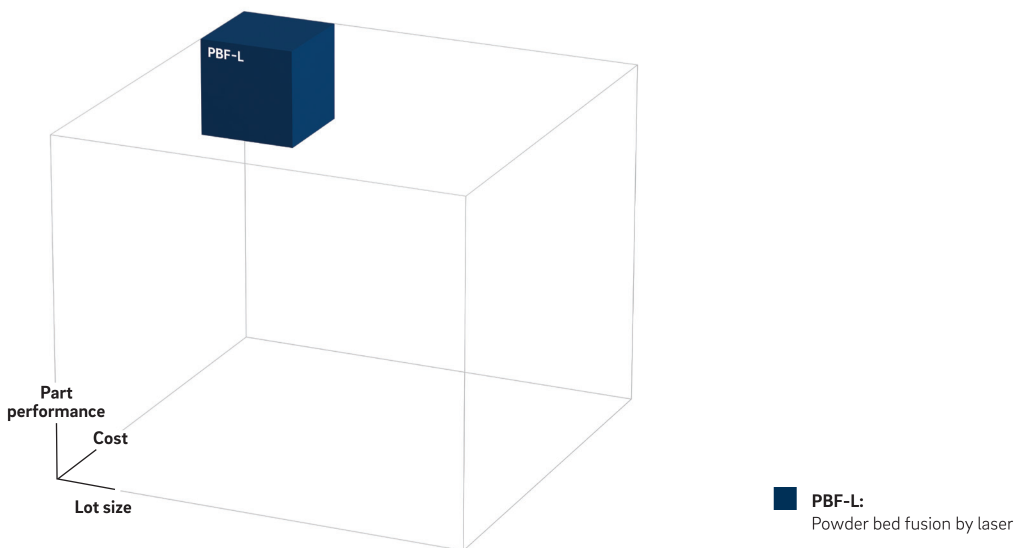
POWDER BED FUSION BY LASER (PBF-L) – PART COSTS WILL NOT FALL BY A FACTOR OF 10

Talk about AM for metal parts and the first thing that comes to mind is powder bed fusion by laser (PBF-L). PBF-L has always formed the nucleus of AM for metal parts and is widely established in the industry. Originally developed in Germany, the market for PBF-L systems is still dominated by three German companies: EOS, SLM Solutions and Concept Laser, the latter now being part of GE Additive since its acquisition by General Electric.

PBF-L is common in the industrial production of highly complex geometries in small batch sizes where

Cover photo: FIT Additive Manufacturing Group

A: Powder bed fusion by laser (PBF-L) within the three dimensions of AM
PBF-L delivers high-performance parts at comparatively high costs



Source: Roland Berger

high performance is required. Typical examples include the production of prototypes, lightweight parts in aerospace and racing or customized products like dental implants, all of which could justifiably be called niche applications. PBF-L is mostly used for manufacturing relatively small parts for which smaller build envelopes are sufficient. The lot sizes depend very much on the specific application, but typically range from a single item – a functional prototype or a custom-made prosthetic implant, for instance – to a few hundred items. Due to the sophisticated equipment technology it requires, PBF-L is an inherently expensive process.

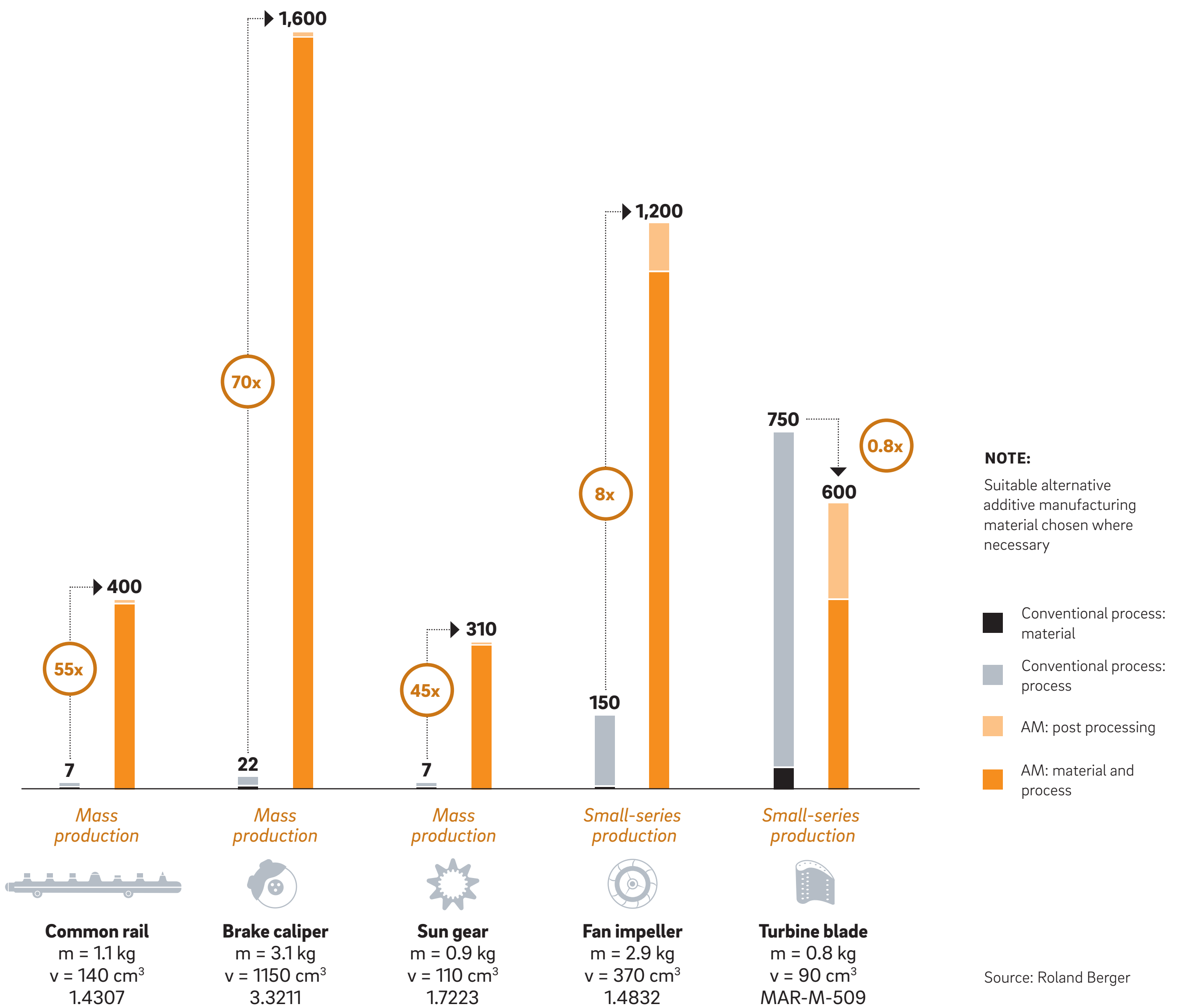
At Roland Berger, we use a cube to demonstrate the complex relationship between the three dimensions of part performance, lot size and cost. Figure A shows where PBF-L is located within this three-dimensional cube. Clearly, much space remains in the cube – space that can potentially be occupied by other technologies, as we discuss below. → A

Compared to conventional manufacturing, PBF-L is still very expensive. A significant gap exists with regard to costs, especially in high-volume applications. Figure B compares the costs for specific metal parts such as common rails, brake calipers, sun gears, fan impellers and turbine blades. For the last of these items, PBF-L costs as much as 70 times more than conventional manufacturing techniques, for example. → B

The productivity of PBF-L is closely linked to the number of lasers that are active at the same time. One producer of PBF-L equipment is currently preparing to launch a

B: Cost comparison

Cost of conventional manufacturing vs. PBF-L, approximation assuming conventional geometries (EUR, schematic)



Source: Roland Berger

new PBF-L machine that will have triple the number of lasers as are available today at a cost that is no more than double the price of an existing machine. This should enable a 20 to 30 percent reduction in the cost of metal parts produced. But for a true commercial breakthrough, radical cost reductions by at least a factor of 10 are required. Only this would make PBF-L competitive with high-pressure die casting and investment casting, for example, and enable its use in large series applications.

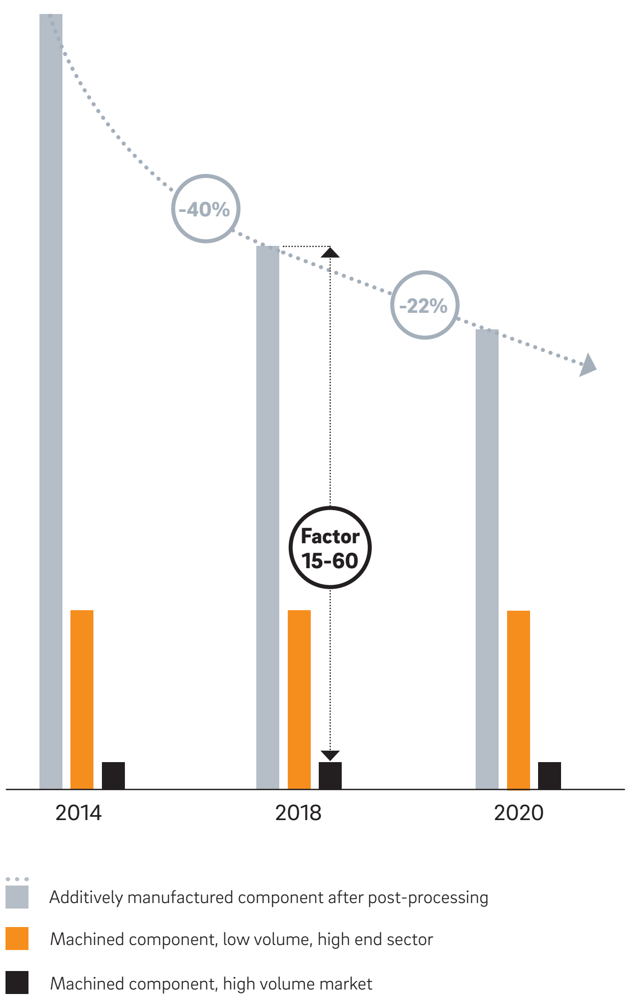
From a technological point of view, significant cost reductions for PBF-L are possible. One innovative approach for example is the multi-spot array technique currently being worked on at the Fraunhofer ILT in Aachen in cooperation with industry partners. However, the system remains at the research stage and the part quality achievable for small structures has yet to be evaluated.

The cost of PBF-L has been falling and will no doubt continue to fall. But major cost reductions of the required order do not appear to be realistic in the next three to five years. Figure C shows the cost trajectory for PBF-L from 2014 to 2020, compared to the degree of cost reduction needed for it to become competitive with conventional manufacturing such as investment casting and machining for medium to large lot size applications. No major breakthrough in part costs is expected in the short term. → C

ALTERNATIVE ADDITIVE MANUFACTURING TECHNOLOGIES

Of course, there is more to AM than PBF-L and its sister technology, power bed fusion by electron beam (PBF-EB), as shown in Figure D. New machine concepts are currently in development offering greater cost efficiency for the AM of metal parts, including in larger lot sizes. Some of these technologies have already reached manufacturing readiness in niche applications, such as direct energy deposition (DED). Others are expected to launch com-

C: No revolutionary part cost reduction expected in the near future
Cost evolution of additive manufacturing by PBF-L vs. conventional manufacturing (schematic)



Source: Roland Berger

D: Established and challenger technologies for metal AM

Several new metal AM technologies are emerging alongside powder bed fusion or direct energy deposition – Simplified overview (schematic)

	POWDER BED FUSION		**DIRECT ENERGY DEPOSITION**
	BY LASER	**BY ELECTRON BEAM**	**POWDER BY LASER**
BUILD PRINCIPLE	Thermal energy by laser fuses regions of a powder bed	Thermal energy by electron beam fuses regions of a powder bed	Fusion of powdered material by melting during deposition
MANUFACTURING READINESS FOR AM	Manufacturing readiness reached for selected industries	Manufacturing readiness reached for selected industries	So far mainly used for coating, AM only in niche applications
KEY MATERIALS	Al, Ti, Ni-alloys, CoCr, steel	Ti, Ni-alloys, CoCr	Ti, Ni-alloys, steel, Co, Al
MECHANICAL PROPERTIES			
POST-PROCESSING REQUIRED	HT[1]/HIP[2], machining, surface treatment	Machining, surface treatment	HT[1], machining, surface treatment
BUILD COSTS			
CORE APPLICATION INDUSTRIES	Aerospace, turbines, med-tech, dental, automotive	Aerospace, turbines, med-tech	Aerospace, general MRO-related business
EQUIPMENT SUPPLIERS (SELECTION)	Concept Laser, Trumpf, EOS, Renishaw, DMG MORI, SLM Solutions, Additive Industries	Arcam	DMG MORI, Mazak, BeAM, PM Innovations, Trumpf, Optomec
	Established technologies		

1) Heat treatment 2) Hot isostatic pressing
Source: Company information; expert interviews; Roland Berger

WIRE BY LASER / PLASMA / EB	MATERIAL JETTING	MATERIAL EXTRUSION	BINDER JETTING
Fusion of wire fed material by melting during deposition	Deposition of droplets of molten metal	Dispensing of material through nozzle to form a green part	Joining powder with binding agent to form a green part
So far mainly used for coating, AM only in niche applications	Production capabilities shown	Production capabilities shown for prototyping	Manufacturing readiness reached for niche applications
Ti, Ni, steel, Co, Al, W, Zr-alloy, CuNi	AL, steel	Cu, Inco, steel, (others incl. Ti in development)	WC, W, CoCr, steel/bronze, steel, Inco, non-metal molds
HT[1], machining, surface treatment	HT[1] (/HIP[2]), machining, surface treatment	HT[1] (/HIP[2]), machining, surface treatment	HT[1] (/HIP[2]), machining, surface treatment
Aerospace, general MRO-related business	Precision engineering, automotive, prototyping	Precision engineering, automotive, prototyping	Precision engineering, automotive, prototyping, med-tech, arts and design
Sciaky, OR Laser, Trumpf, Norsk Titanium	Vader Systems, XJet	Desktop Metal, Markforged, BASF	ExOne, Digital Metal, Desktop Metal

Challenger technologies

Low degree required

High degree required

Low – High

Full rate production

Proof of concept

"In order to become cost competitive with conventional manufacturing for a wide range of use cases, the cost of additive manufacturing would need to decrease by at least a factor of 10. So far we do not see the signs of such structural decreases within the established portfolio of additive manufacturing technologies but the race is on for the next big thing."

Bernhard Langefeld

mercially in 2019 or later, such as material jetting (MJ), material extrusion (EXT) and binder jetting (BJ). At the moment, these technologies complement PBF-L, targeting niches that are not covered by it. In the long-term, however, they could extend their application and partially replace PBF-L. → D

Placing these other technologies alongside PBF-L within our cube provides some interesting insights (Figure E). Each new technology currently occupies its own position with regard to part performance, lot size and costs. Companies can use this as a basis for determining which technology is best suited for a particular project. → E

The field of AM is evolving fast. It remains to be seen how each technology will shift or expand within the cube in the future.

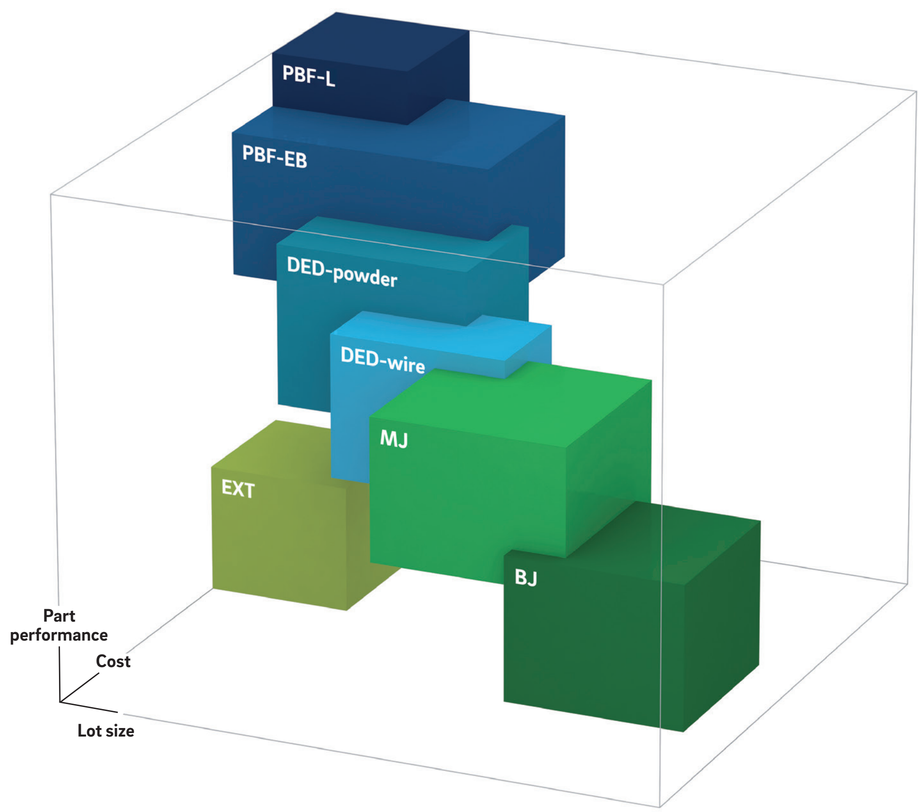
DEVELOPING A TECHNOLOGY ROADMAP

The technological developments described above have major implications for the future of metal manufacturing. AM is on the brink of industrialization. The question for companies is, which technology will ultimately dominate the cube? In other words, which technology should you place your bets on?

It remains to be seen whether PBF-L, as the core technology for high-performance applications, will be partly or fully replaced by the new contenders. True, the new concepts have the advantage that, from a cost perspective, they are less burdened down by expensive equipment and technological complexity and may thus be able to overtake PBF-L. New technologies could be 100 or more times faster than PBF-L and produce parts at a fraction of the cost. But at the same time, increased competition may also spur innovation from established PBF-L machine manufacturers, leading to improvements in the incumbent technology that help it retain its current dominant position.

The most likely scenario, we believe, is not that of a

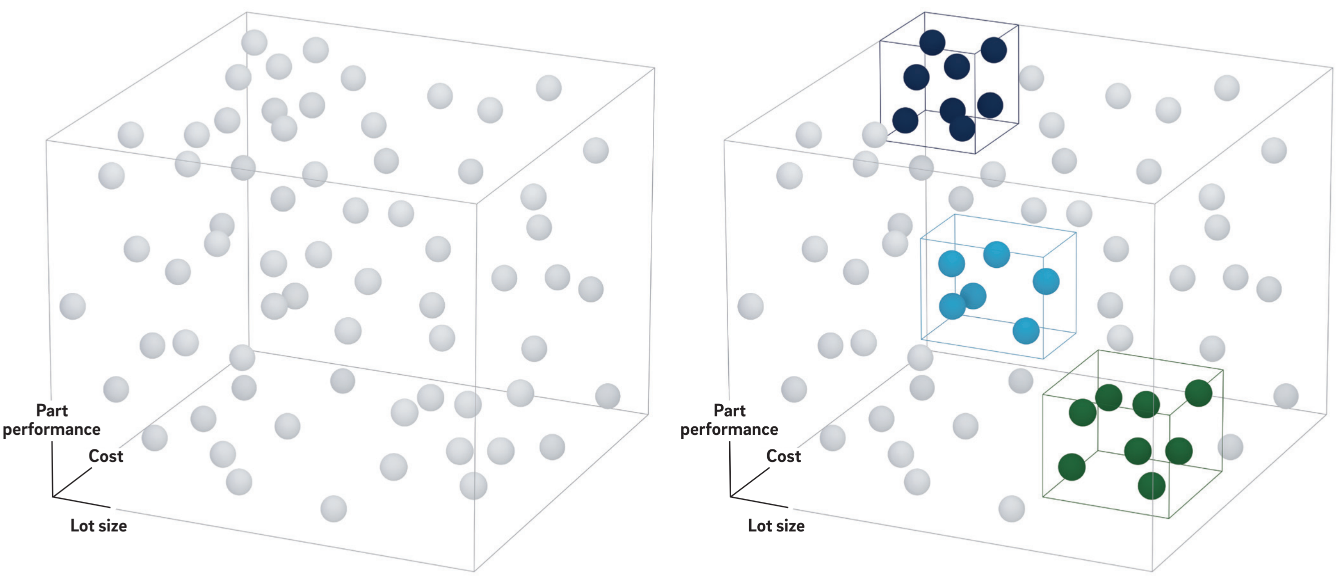
E: Current status of major AM technologies
Metal AM technologies in the cube (schematic)



- **PBF-L:** Powder bed fusion by laser
- **PBF-EB:** Powder bed fusion by electron beam
- **DED-powder:** Direct energy deposition powder by laser
- **DED-wire:** Direct energy deposition wire by laser
- **MJ:** Material jetting
- **BJ:** Binder jetting
- **EXT:** Material extrusion

Source: Roland Berger

F: Evaluation and clustering of part portfolio
Steps 2 & 3 (exemplary and schematic)



Source: Roland Berger

Your part portfolio: Potential AM use cases

Cluster 1: High performance requirements at small lot sizes and high cost tolerance (e.g. PBF-L)

Cluster 2: Medium to high performance requirements at small to medium lot sizes and medium cost tolerance (e.g. DED)

Cluster 3: Lower performance requirements at higher lot sizes and lower cost tolerance (e.g. binder jetting)

3D-Illustrations: Padraic Rapp

single technology ousting all the rest. More likely a range of technologies will coexist, each meeting different customer needs. With the entire AM landscape rapidly changing and opening up new opportunities, manufacturing companies need to assess the impact that AM will have on their business. To help them develop a technology roadmap as part of a technology strategy reflecting the diversity of AM technologies, we suggest the four-step approach outlined below.

STEP 1
SCREEN THE FULL SOLUTION SPACE.
The first step is to screen the full range of technologies already available or close to achieving maturity. It is vital to develop a detailed understanding of what each one has to offer and whether it might be relevant for your particular business. The information presented in Figure D (above) can serve as a useful starting point.

STEP 2
EVALUATE USE CASES.
Once you have a handle on the technology landscape, you should systematically go through your product portfolio identifying potential use cases for AM along the entire value chain. Plot these use cases in the cube according to their requirements regarding part performance, lot size and cost (see cube on the left in Figure F). Be sure to look beyond the production of specific parts and include applications in engineering, from prototyping to aftersales. Software algorithms can help identify suitable parts for AM by scanning drawings of parts and assemblies for certain criteria, but you must also consider the strategic impact of AM on your business.

STEP 3
CLUSTER USE CASES AND CREATE YOUR TECHNOLOGY ROADMAP.
The third step is to cluster the use cases from Step 2 within the cube (see cube on the right in Figure F). Note that some use cases may be located in areas that are still "blank" in the cube. As technologies expand or shift and new technologies emerge, those areas may fill up. Assess each cluster based on its potential impact on your products and organization. Then, cluster by cluster, draw up your technology roadmap, indicating at what point in time and under which conditions you would be prepared to invest in AM for each cluster. → F

STEP 4
INSTITUTIONALIZE REGULAR UPDATES.
Finally, establish a regular screening process as a basis for updating your technology roadmap. This makes the entire four-step process a circular one, enabling you to stay on top of technological advances and take their broader implications into account.

With AM on the brink of industrialization, companies need to understand the advantages of established AM technology and where it can meet their needs. At the same time, they must keep an eye on new and alternative technologies in case any of them become more relevant for their particular business. Finally, a technology roadmap, developed with the help of the four-step process we outline above, can help them shape their technology strategy going forward.

WE WELCOME YOUR QUESTIONS, COMMENTS AND SUGGESTIONS

AUTHORS

DR.-ING. BERNHARD LANGEFELD
Partner
+49 160 744-6143
bernhard.langefeld@rolandberger.com

DR.-ING. MARKUS MOEHRLE
Project Manager
+49 160 744-2148
markus.moehrle@rolandberger.com

CHRISTOPH BALZER
Senior Consultant
+49 160 744-2937
christoph.balzer@rolandberger.com

PETER SCHILDBACH
Consultant
+49 160 744-6165
peter.schildbach@rolandberger.com

PUBLISHER

Roland Berger GmbH
Sederanger 1
80538 Munich
Germany
+49 89 9230-0

More information to be found here: www.rolandberger.com