Roland Berger

Additive Manufacturing – next generation AMnx

21. Fachtagung Rapid Prototyping, OWL Lemgo

Hochschule Ostwestfalen-Lippe
University of Applied Sciences

November, 4th, 2016

Photo: FIT AG

Roland Berger is a trusted advisor for Additive Manufacturing (AM) in the Engineered Products & High Tech industry

AMnx @ Roland Berger

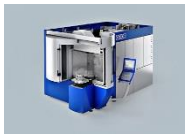
50 offices
in 36 countries
– 2,400 employees

> Founded in 1969 as a one-man business, we now have successful operations in all major international markets
> Largest consulting firm with European/German roots
> Among the top 3 players for strategy consulting in Europe, number 1 for mechanical & plant engineering
> Team of 2,400 employees worldwide, of whom 180 are partners

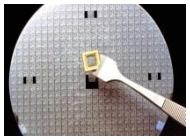
Engineered Products & High Tech Competence Center


Aerospace & defense


Energy equipment


Long lifecycle products


Digital technologies

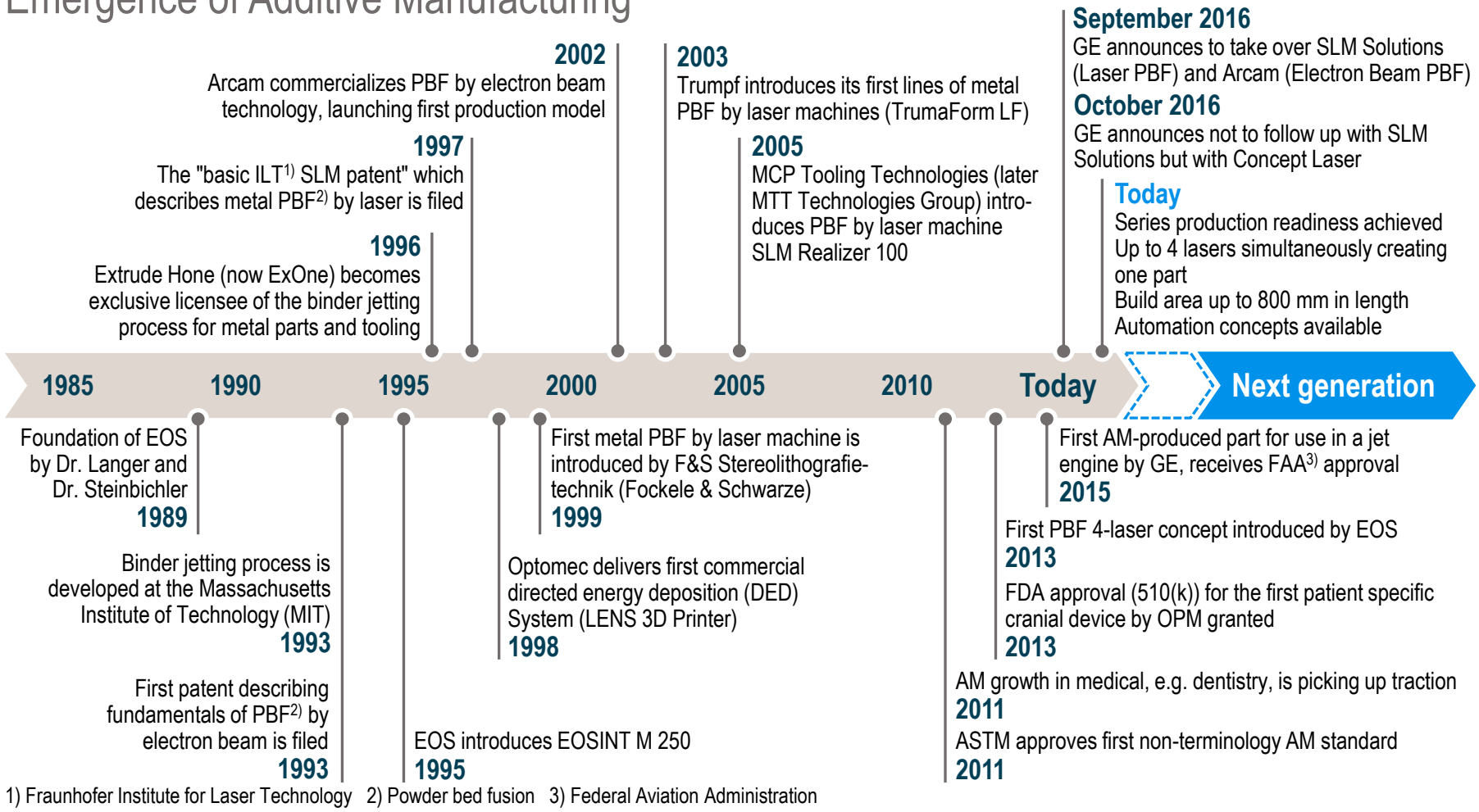

B2B electronics

> Additive Manufacturing is part of our digitization initiative
> Roland Berger published two AM studies in 2013 and 2016 available on our homepage
> Relevant project experience ever since forms the basis for the updated study at hand
> Our consulting services for AM range from business development to operational excellence

Source: Brand Eins; Roland Berger

AM has seen strong development in the recent past and achieved production readiness – What's next (AMnx)?

Emergence of Additive Manufacturing



1) Fraunhofer Institute for Laser Technology 2) Powder bed fusion 3) Federal Aviation Administration

Source: Company websites; European Patent Office; Wohlers Associates; Roland Berger

GE has announced on September 6th to buy SLM Solutions and Arcam and explained the underlying (engineering) rational

GE investements into PBF[1)] by laser and electron beam

Following the GE Additive Manufacturing Investor Meeting the acquisition fit into GE's overall business model due to

> AM system integration capabilities (component reduction for e.g. turbine frames, nozzles, etc.)

> Strong GE internal consumption of AM components in (aerospace) turbines, Healthcare, O&G and Service. Demand of ~1.000 machines expected for upcoming 10 years, 3-5 $bn internal cost out opportunities identified

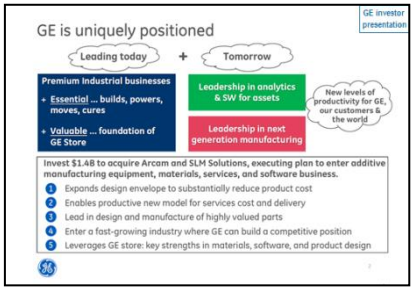
> Commercialization of the GE material and process experience; leverages of the Know-How from the acquisition of Morris Technology in 2012

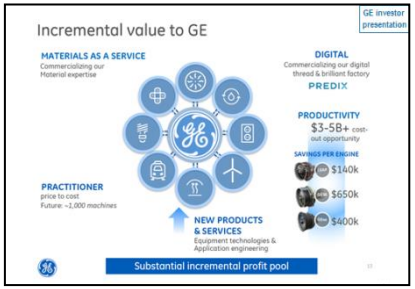
> Set up of new products and services

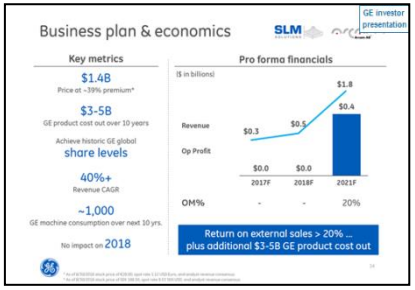
> Expand digital services like PREDIX, create closed loop equipment control and monitoring

> Contribution to the overall GE Store (GE technical offering)

> GE expects 20% operational profit on the SLM Solution and Arcam deal from 2021 onwards







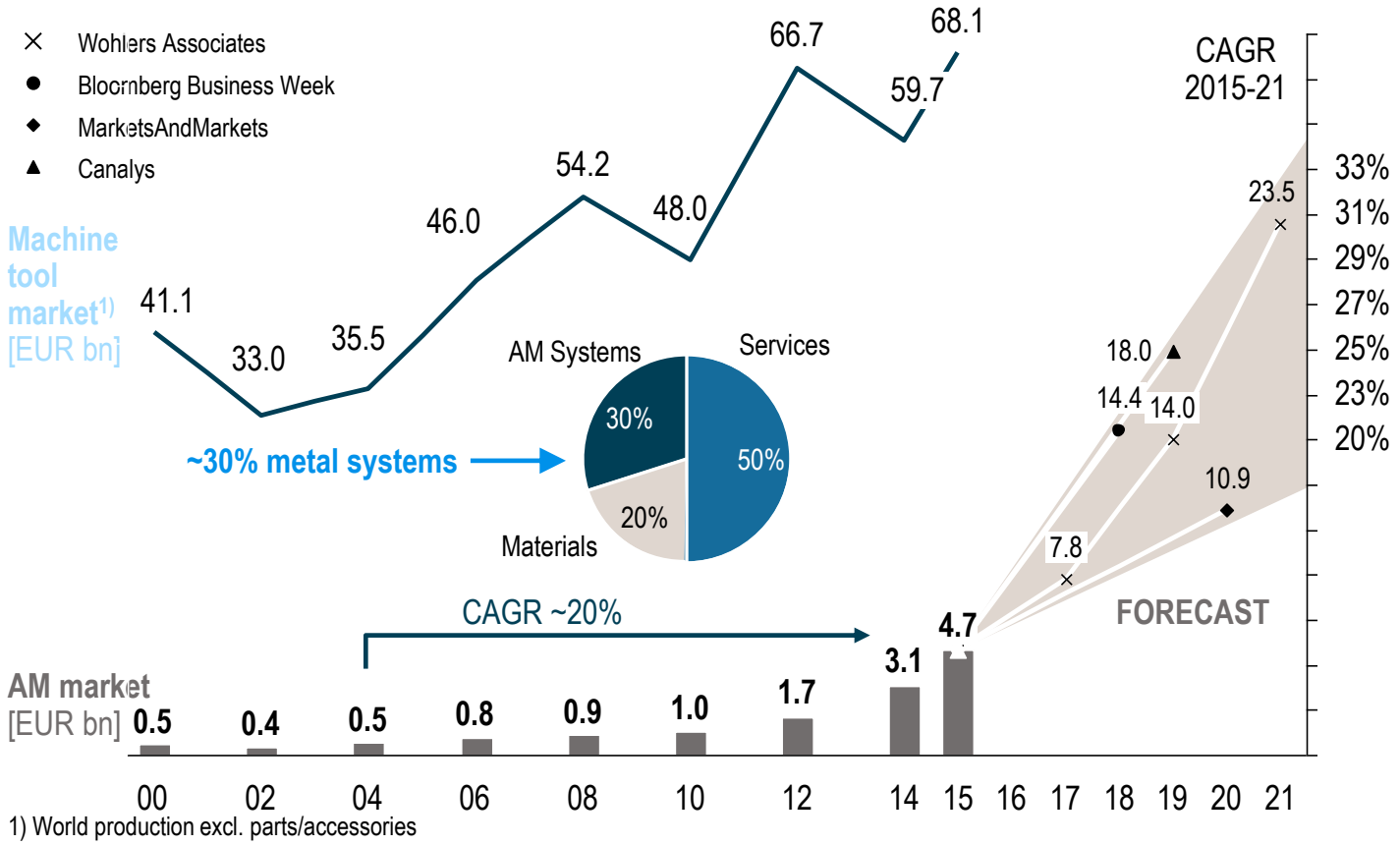
1) powder bed fusion

Source: GE Additive Manufacturing Investor Meeting

Global AM market is expected to grow significantly until 2021 – Growth rates of up to 40% per year expected by researchers

Global AM market

Development AM market 2000-2021 [EUR m]



1) World production excl. parts/accessories

Comments

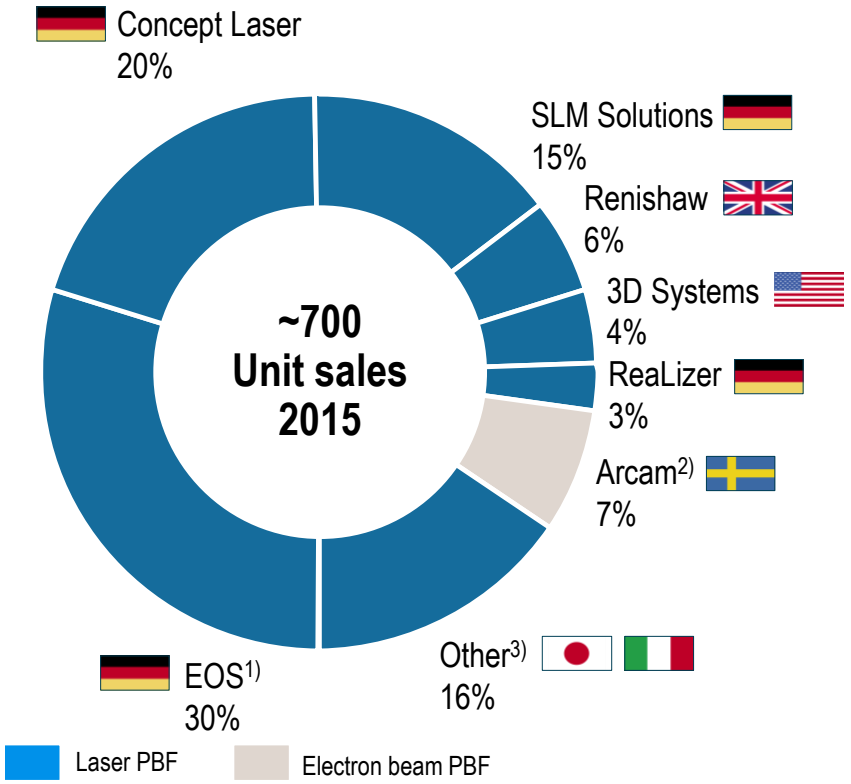
- Compared to the machine tool market, the 2015 metal AM system market is still small at less than 1%
- For the period 2004 to 2015, the overall AM market showed an annual growth rate (CAGR) of approx. 20%, while from 2010 to 2015 the growth rate (CAGR) was higher than 30%
- Based on different estimates the market is expected to multiply by factor two to five until 2021
- Exchange rates per Bundesbank

Source: Expert interviews; Wohlers Associates (2016); VDW (2016); Bloomberg Business Week (2014); Canalys (2015); MarketsAndMarkets (2014); Roland Berger

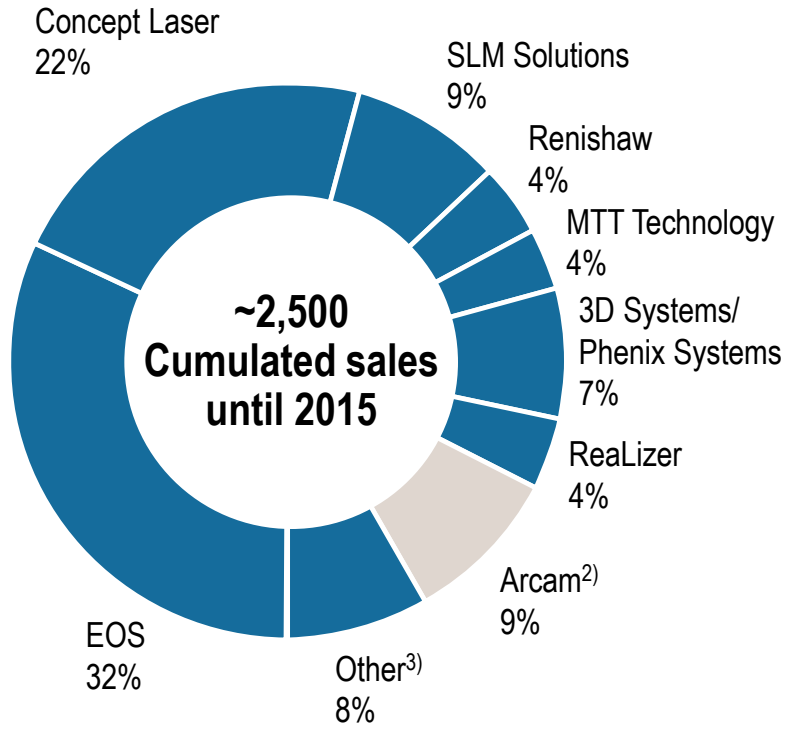
Metal PBF market is dominated by German players EOS, SLM Solutions and Concept Laser – Other players still relatively minor

PBF system suppliers

Metal AM systems (PBF) sold in 2015



Metal AM systems (PBF) cumulated sales until 2015



1) Estimated share of metal systems 2) PBF by electron beam 3) Other laser PBF sales: Matsuura (JPN), OPM Lab (JPN), Sisma (ITA) and several smaller players
4) Metal AM activities now part of SLM Solutions and Renishaw 5) Phenix Systems was acquired by 3D Systems in 2013
Source: Wohlers Associates; Roland Berger

Roland Berger is seen as the "Thought Leader" in AM. Our studies and publications are recognized by the AM community

"Additive Manufacturing – next generation (AMnx)" – our latest study

Engineering & software
- Next generation engineering
- SCRUM engineering
- **AM software**
- Bionic design

Chapter **A.**

Materials
- **Amorphous metals**
- **Metalysis process**
- Multi-material parts

Chapter **B.**

Machines
- **Multi-laser concepts**
- Full powder-bed illumination
- Hybrid applications
- Electron Beam Melting
- Automation concepts
- Materialize Controller
- **Sand binder jetting**
- AM process control
- **Health risks in AM factories**[1)]

Chapter **C.**

Post processing
- MMP technology
- Computer tomography in quality inspection

Chapter **D.**

Services
- AM gas burner tip repair
- AM for mobile repair

Chapter **E.**

IMPACT
- AM cost model
- AM market development
- **Stock market**

Chapters **F.-H.**

1) Not included in published study

Source: Roland Berger

A. Engineering & software

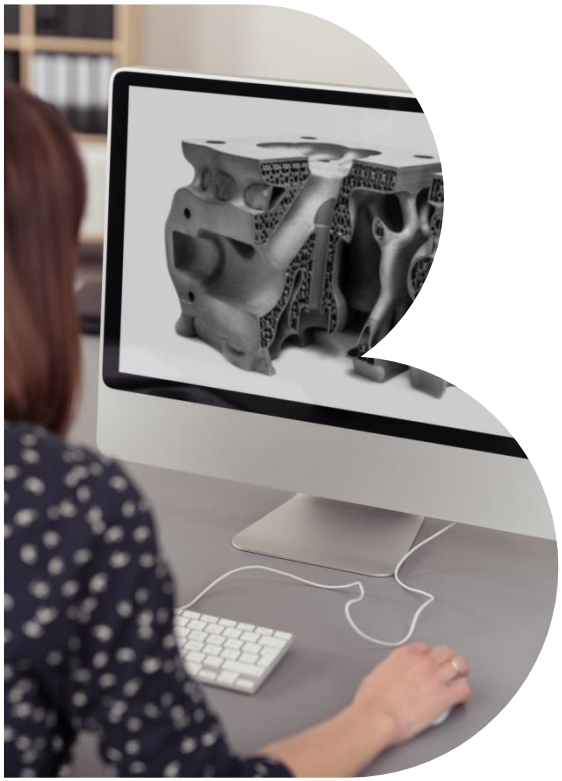


Photo: FIT AG (cylinder head)

How will the fast availability of AM prototypes and the minor relevance of manufacturing impact new engineering processes?

Next generation engineering

Products

- The value of mechanical components is falling in favor of software functionalities and automation technology
- Overall relevance of software and number of software developers is rising
- Production and information technology are merging closer together (resulting in Industry 4.0; Internet of Things)

Lifecycle requirements

- Product lifecycle is getting shorter, sometimes even shorter than the development time
- Rising number of variants per product
- Trend toward mass customization

Engineering environment

- Global engineering teams, working 24/7
- Collaboration with external engineering suppliers
- Rising complexity of customer requirements
- AM simplifies formerly complex manufacturing processes ("CAD model = product")

Rapid prototyping

Faster availability of prototypes due to Additive Manufacturing

Impact

Engineering software

CAD/CAM/PLM

FEA, various simulation tools, specific AM software

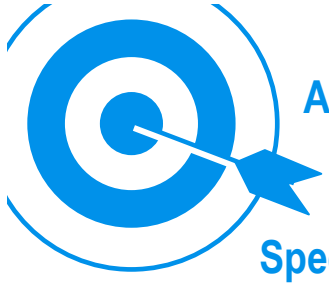
Virtual reality

Will traditional engineering become more and more like software engineering due to the higher relevance of software in our products and the stronger support of software in AM development/manufacturing processes?

Source: Rennteam Uni Stuttgart (Photo); Roland Berger

SCRUM is an agile project management methodology that breaks deliverables down into incremental sprint backlogs

Targets and principals of SCRUM

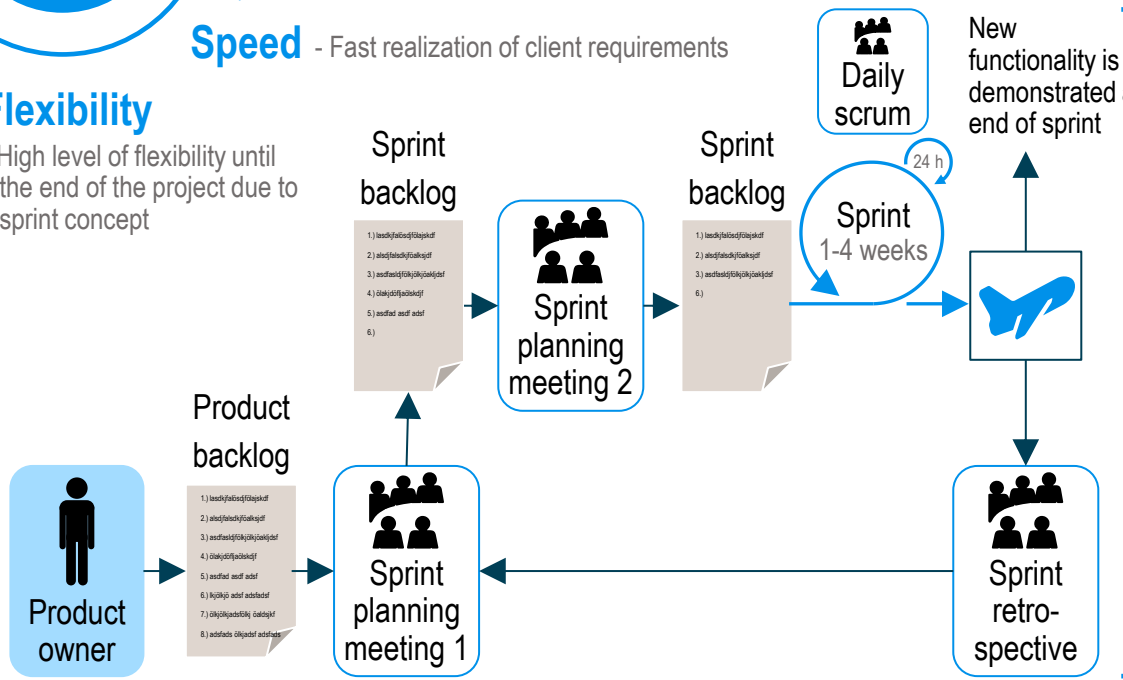


Agility - Keep projects agile/lean by clear prioritization of tasks for each sprint

Speed - Fast realization of client requirements

Flexibility

- High level of flexibility until the end of the project due to sprint concept

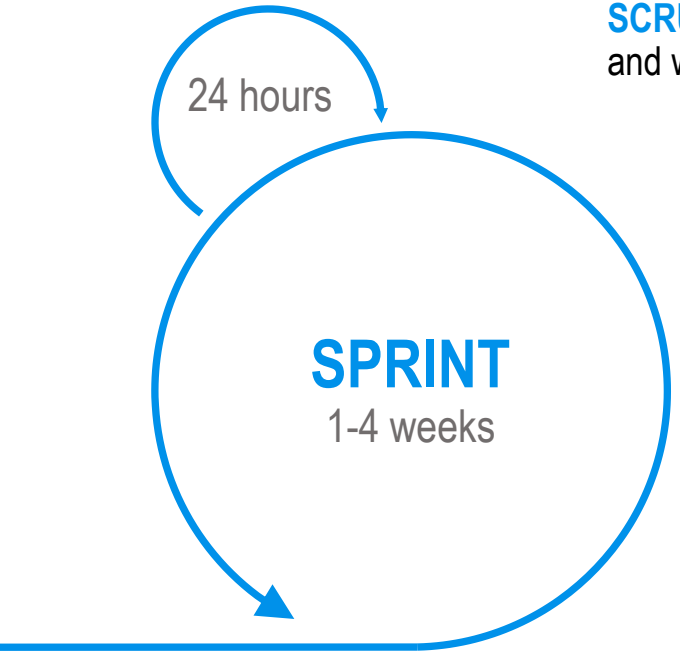


- > Each sprint delivers a working product, duration of a sprint is timeboxed
- > Close client involvement, client is involved in prioritization for each iteration
- > Detailed specifications are only released if really needed for an iteration
- > Process learnings are carried over from iteration to iteration, leading to continuous improvement
- > Frequent delivery of results (releases) and high process transparency
- > High level of team involvement and consequently a highly motivated project team

Source: Roland Berger

Initially developed for software engineering, SCRUM will have a huge impact on traditional engineering projects in the future

Key characteristics and facts about SCRUM



SCRUM was developed in the early **1990s** in the US and is today one of the most popular and well known **frameworks for software development**

SCRUM uses small self-organizing **teams** and is most efficient for **complex projects** with more than 4 developers

SCRUM consists of a clear set of **rules and roles**, supporting the **self-organization** and efficiency of the team – the roles are: Product Owner, Team and SCRUM Master

At the end of each **sprint** a working product that is 'really done' is available – the product is **reviewed by the whole team** and product and process learnings are carried forward into the next sprint

Sprints are of **fixed duration** and never extended – **"timeboxed"**

Additive Manufacturing will make the **SCRUM methodology** applicable to traditional engineering processes by providing (several, functional) **prototypes within a sprint iteration**

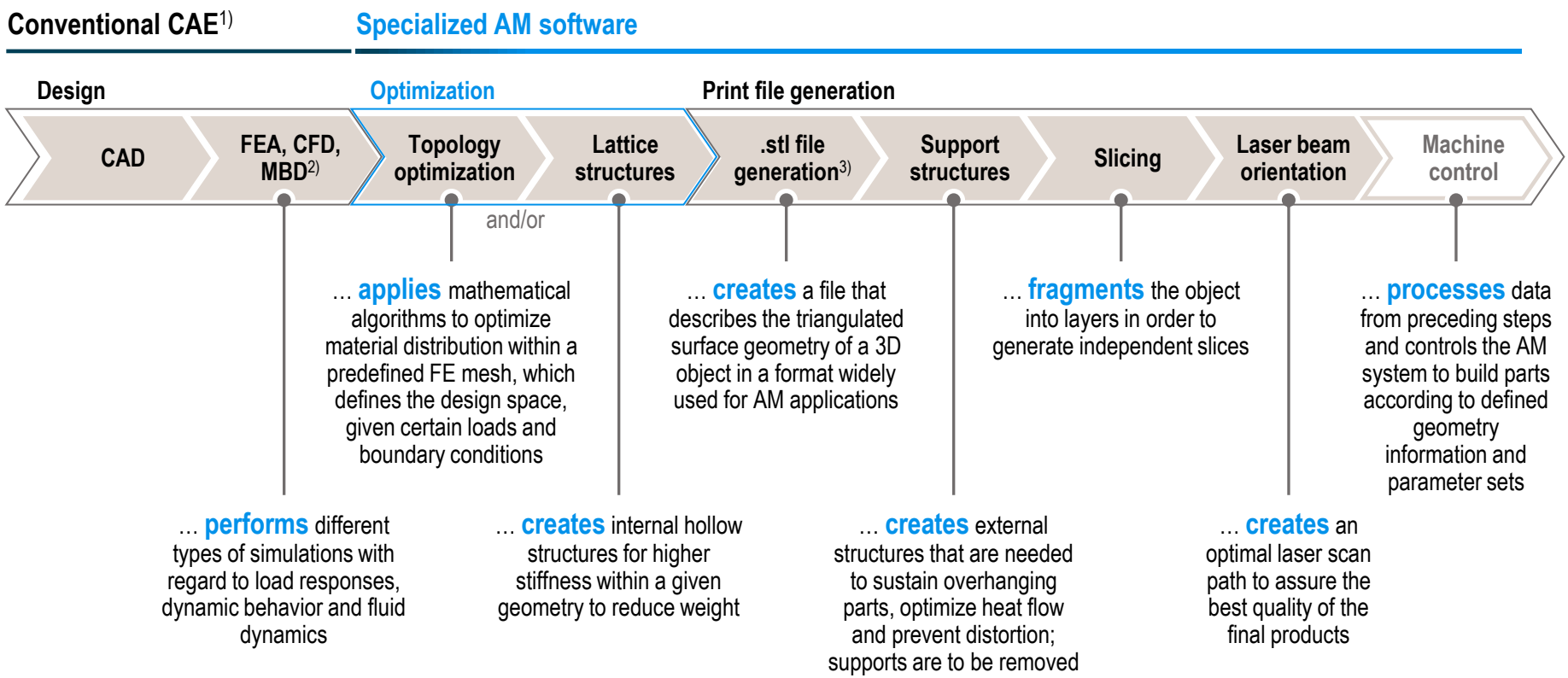
These **opportunities** need **to be reflected** in the processes and organization of **future engineering departments**

!

Source: Roland Berger

In order to develop AM-ready components, the conventional CAE[1] needs to be complemented by specialized AM software

Typical AM software process chain

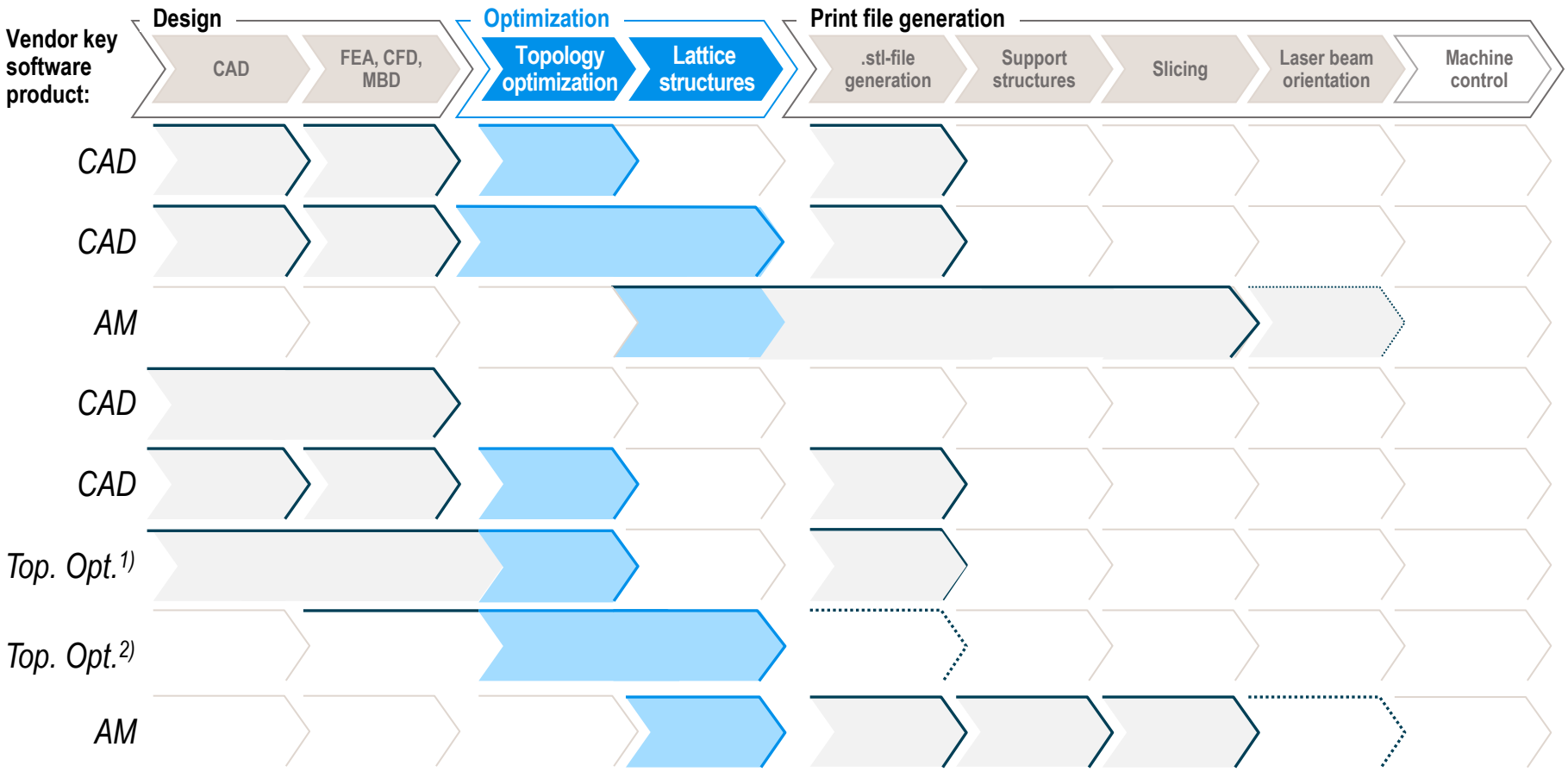


1) Computer-Aided Engineering 2) Finite Element Analysis, Computational Fluid Dynamics, Multibody Dynamics 3) Or other suitable format

Source: Roland Berger

Topology optimization & lattice structures software is available from different vendors – Level of sophistication varies by solution

AM software supplier landscape (sanitized, non-exhaustive)



1) Topology Optimization 2) extended scope in partner alliance

Source: Roland Berger

The terms bionic design and topology optimization represent different approaches but can also go hand in hand in practice

Bionic design and topology optimization

The approach of bionic design…

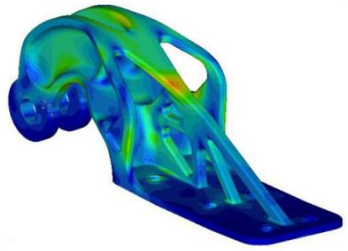
- **Evolution** has left most living organisms **highly optimized and efficient**
- **Material** is only applied where **functionally required**
- Instead of **solid parts,** combinations of a **surface** of varying thickness and a **porous structure** beneath can often be found
- For example, the **bone of a bird** is highly lightweight due to large air cavities, yet very rigid
- The systematic generalization and **transfer of suitable design principles observed in nature** to technical systems is often referred to as bionic design

Bone of a bird

Underside of a water lily

…compared to topology optimization

- Topology optimizers apply **mathematical algorithms** to derive optimal designs with respect to given loads and boundary conditions
- Resulting geometries can look **similar** to bionic designs
- When it comes to very **fine structures**, the approach is limited by the highest feasible FEA mesh resolution
- Findings from the field of **bionic design** can provide new **ideas and impulses** for the formulation of topology optimization problems, e.g. making it possible to **target certain design principles** as optimization results



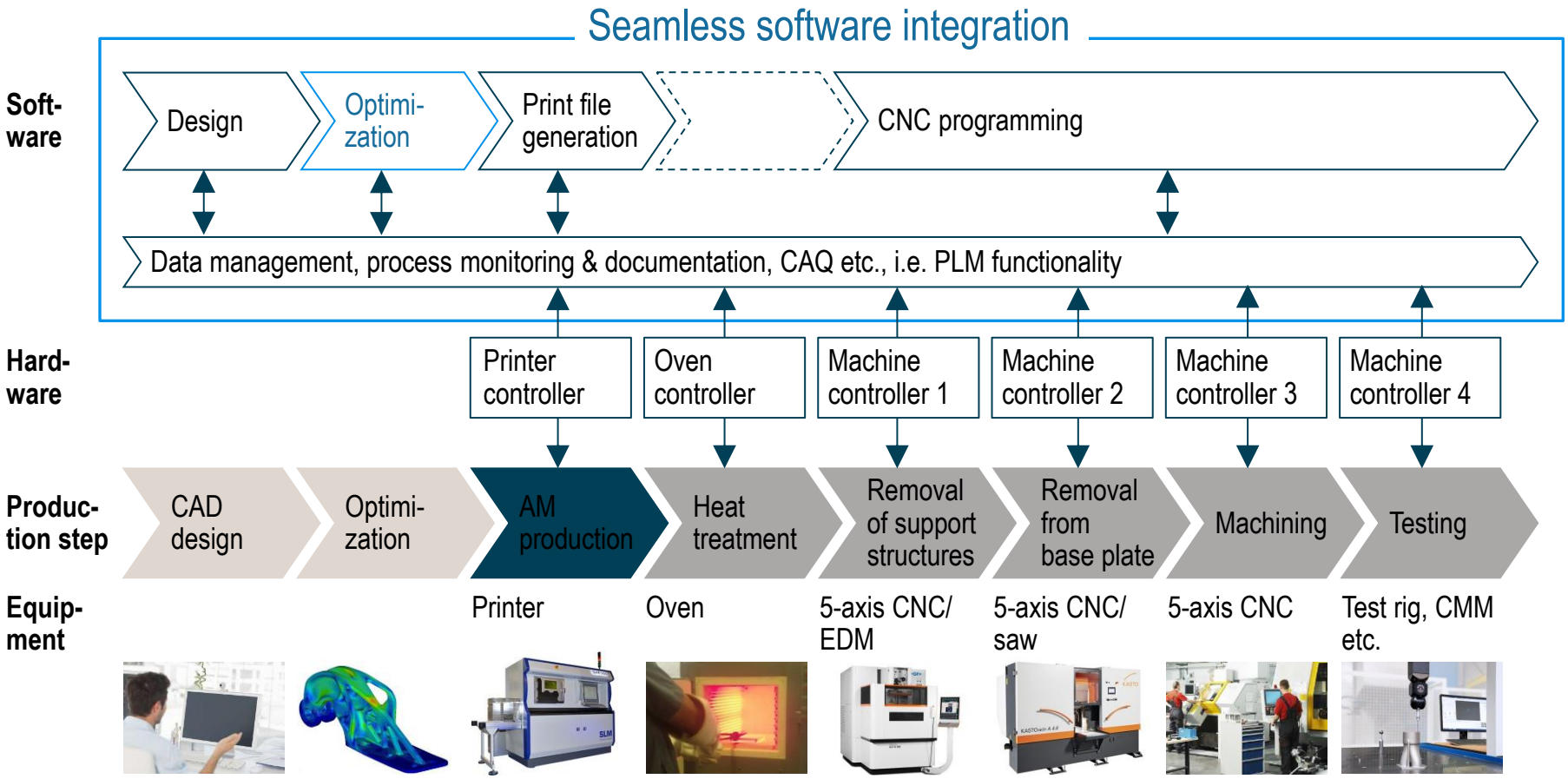
Topology optimized nacelle hinge bracket (Source: Altair/EADS)

Engine block with minimized material usage (Source: Autodesk)

Source: Altair; Autodesk; EADS; Roland Berger

For future applications a seamless software suite needs to cover the entire AM value chain including e.g. machining and documentation

Seamless AM software suite – schematic



Source: Roland Berger

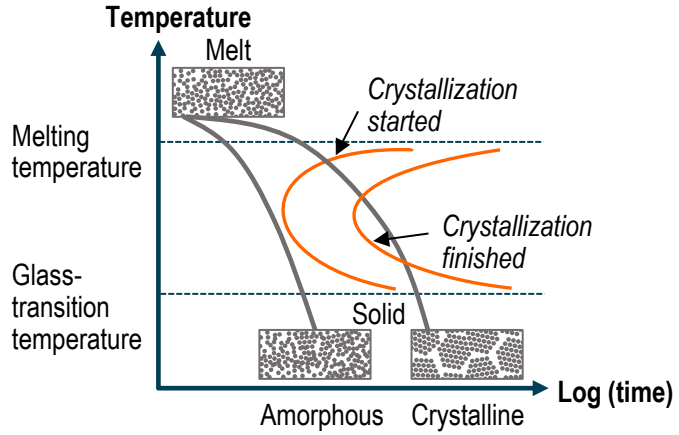
B. Materials

Photo: AIRBUS APWORKS GmbH

Amorphous metals offer a unique combination of material properties due to their atomic structure

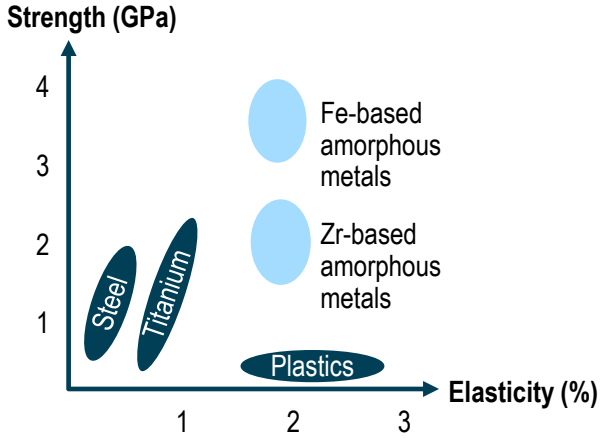
Amorphous metals: Introduction

Metallurgical process



- Alloy with suitable **glass-forming ability** needed to produce amorphous metals, e.g. Fe-, Zr- or Ti-based
- High cooling rates lead to amorphous (non-crystalline, i.e. disordered) atomic structure
- Achievable cooling rate limits **maximum material thickness** with traditional manufacturing methods, e.g. casting
- The amorphous atomic structure determines specific material characteristics

Mechanical properties



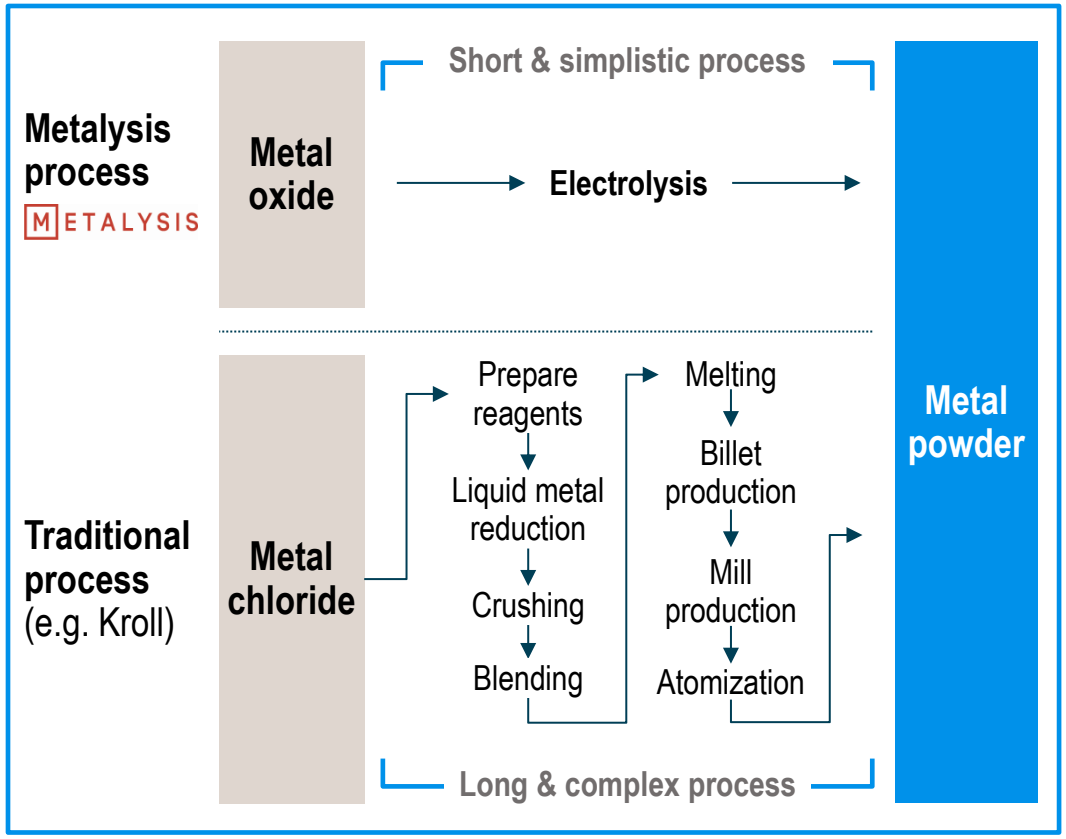
- Amorphous metals combine **high strength and high elasticity**
- They offer high hardness, corrosion resistance, conductibility, biocompatibility and self-sharpening properties
- **Ductility and fatigue strength** are typically below that of crystalline metal – research has shown that fatigue strength can be improved by reinforcing amorphous matrix with nanocrystals
- Ferromagnetic amorphous alloys furthermore offer **high magnetic susceptibility with low coercivity** and high electrical resistance

Source: Exmet; Roland Berger

UK technology start-up Metalysis invented a shortened production process for metal powder using electrolysis

Metalysis process vs. traditional process

Comparison of process steps



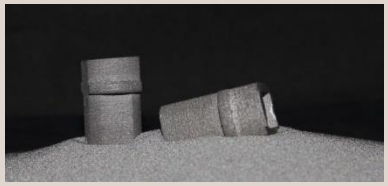
Benefits of Metalysis process

Clean technology
> No toxic byproducts, lower energy consumption and reduced CO_2 footprint

Cost effective
> Fewer process steps – lower investment and operating cost
> High yield process with tailored particle sizes
> Cost reduction of 75%+ conceivable

Transformational
> Solid-state alloying: ideal for different densities and melting points

> Metalysis are engaged in a development project with GKN Aerospace for aerospace-tailored titanium alloy AM powder



Demonstration component for an automotive turbocharger made from Metalysis titanium powder, produced on a Renishaw PBF machine

Source: Metalysis; Roland Berger

C. Machines

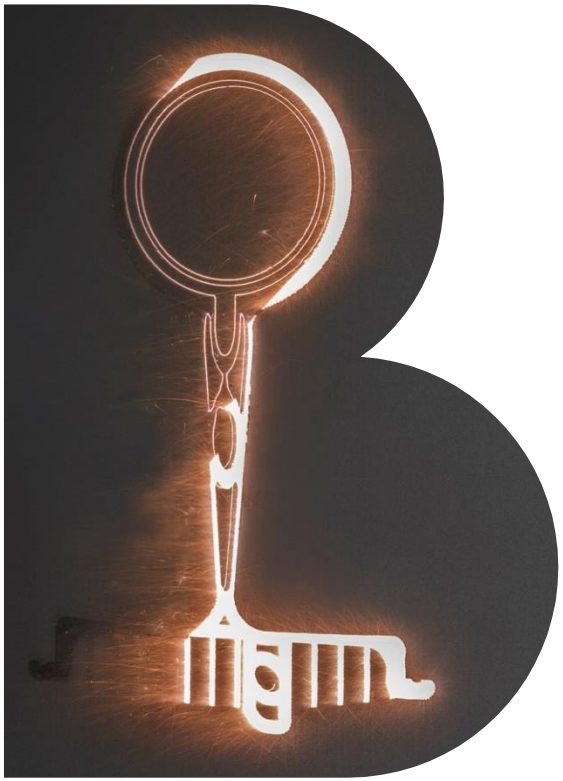


Photo: Concept Laser

Current AM systems utilize multiple lasers to increase productivity and reduce manufacturing time

Multi-laser concept – The current state-of-the-art solution

Principle

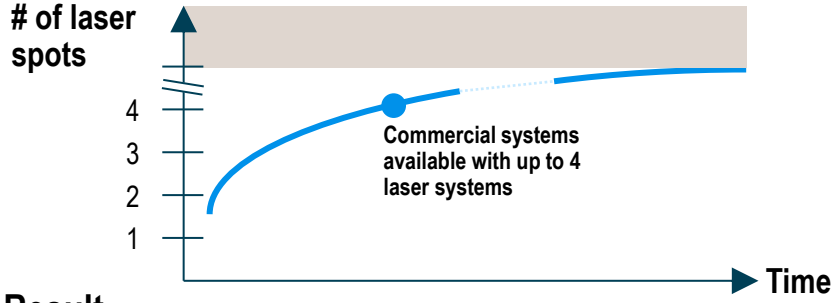
> AM **production time depends on** the layer-by-layer **laser exposure time**, lowering of the chamber platform and powder-bed distribution time

> Using **multiple independent lasers**, different **areas** can be **manufactured in parallel** with direct impact on exposure time

– E.g. dual-laser systems halve the exposure time leading to an overall **productivity increase** by a **factor of 1.8**

Image of the manufacturing chamber of SLM Solution's SLM 500HL system capable of using 4 independent lasers and scanner systems simultaneously

Realization



Result

> A **higher number of laser spots** yields a direct **increase in manufacturing speed**

> Nevertheless, multi-laser technology faces some **problems**, e.g.:

– The **laser system** is the system's **most complex and expensive** component

– **Heat and fume creation** scales with the number of laser spots and **limits the manufacturing process**

> **Limited advantage of multi-laser technology**: scaling of the system with the most complex and expensive component fundamentally limits the method's cost advantage

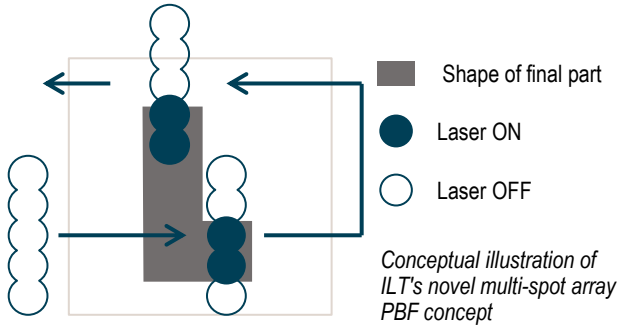
Source: SLM Solutions; Roland Berger

ILT's multi-spot system represents a conceptually new approach – Direct advantages in process speed and system cost

Multi-spot array concept – Next generation technology

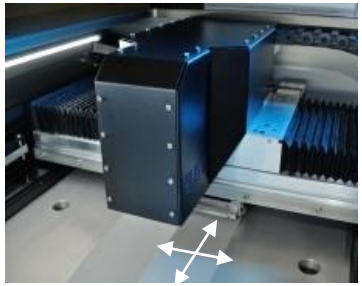
Principle

- A 5-spot **laser array** is mounted **on a single printer-like processing head**
- **5 diode lasers** are **coupled** to the processing head **via** an **optical fiber** system
- The processing head **moves** over the powder bed **similarly** to a **paper printer head**
- A **local shielding gas and fume removal** system is mounted **directly on** the **processing head**
- **Melt pool control** is achieved **by laser intensity modulation** while the processing head moves over the powder bed (see figure below)

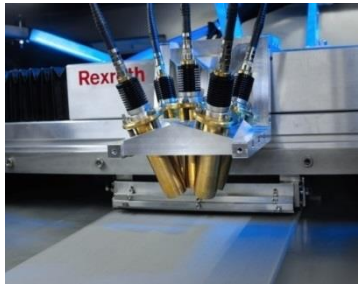


Conceptual illustration of ILT's novel multi-spot array PBF concept

Realization



Picture of the enclosed ready-to-use PBF multi-spot system



View of the processing head: a five-spot array is mounted on a single scanning head

Result

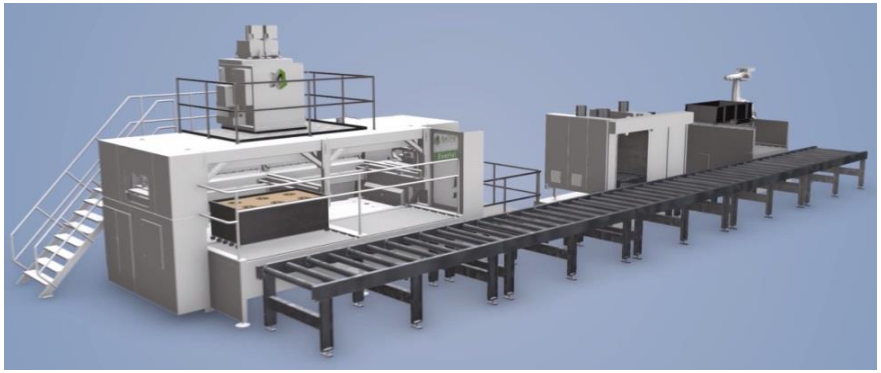
- **Good scalability** in terms of manufacturing speed and chamber size:
  - **Increased manufacturing speed** due to a wider area of optical illumination
  - **Chamber size** is **not limited** by the optical system
  - Local shielding gas and fume removal system for **ideal processing conditions independent of chamber size**
- **Reduced system cost** due to a low-complexity optical system

System currently in **research stage**, part **quality to be evaluated** – potential drawbacks vs. beam-steering approach for small structures

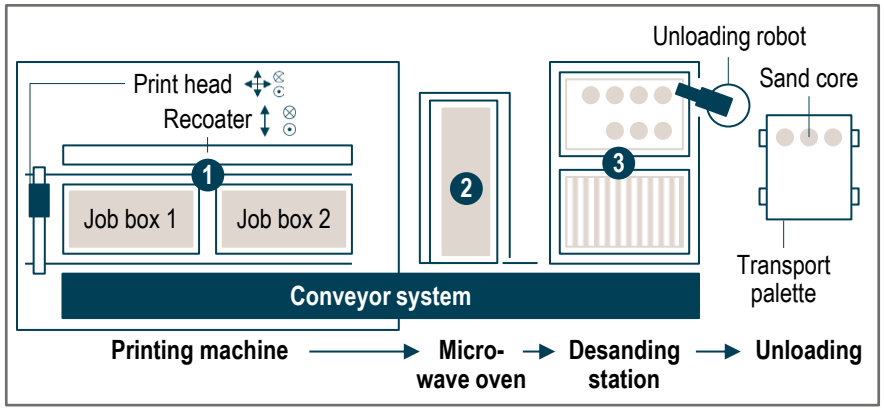
Source: Fraunhofer Institute for Laser Technology (ILT); Roland Berger

ExOne has developed a fully automatic production line for silica sand cores using soluble glass as binder

Full line concept for serial production by ExOne



Production line concept (3D simulation)



Process flow and machine setup

Working principle

> The new machine concept by ExOne addresses the cost effective production of silica sand cores, which are difficult or impossible to manufacture by alternative processes due to their geometric complexity

> ExOne provides a full line concept for serial production including one or more Exerial 3D printers (1), a curing and drying microwave station (2) and a desanding station with an unloading robot (3). The printer is equipped with two job boxes (2,200 x 1,200 x 700 mm^3), which are moved by a conveyor system from station to station. Multiple configurations of the different elements are possible

> The drying and curing of the environmentally friendly soluble glass binder material takes place in a microwave furnace

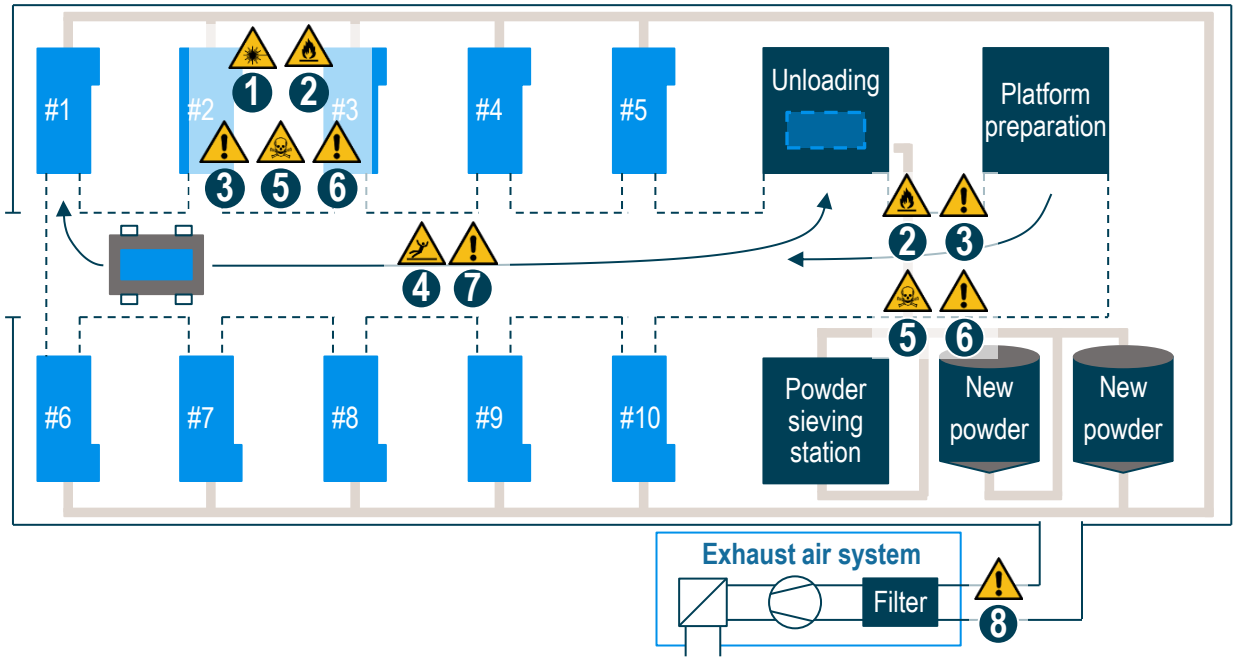
> The build speed is in the range of 300-400 l/h, max. resolution of 0.1 mm and layer thicknesses from 0.28 to 0.5 mm

> The current print head has a width of 600 mm, which means two runs to fully print the 1200 mm wide job box. A 1200 mm print head is expected to become available in 2016, which would boost the efficiency of the overall system close to the cost level of conventional automotive serial production

Source: ExOne; Roland Berger

Health risks from AM are not yet sufficiently well understood, especially with regards to the handling of metal powders

Health risks in AM factories (non-exhaustive)



Health risks from Additive Manufacturing

1. Danger to eyes and body from AM machine laser system
2. Fire & explosion hazard from metal powders
3. Risk of chemical reactions from metal powders
4. Danger of slipping e.g. due to scattered metal powders
5. Risk of metal toxicity via powder inhalation, eye or skin contact
6. Risk of serious eye irritation & damage from metal powders
7. Suffocation risk from oxygen displacement by inert gases
8. Deposition of metal powders in filter systems and piping

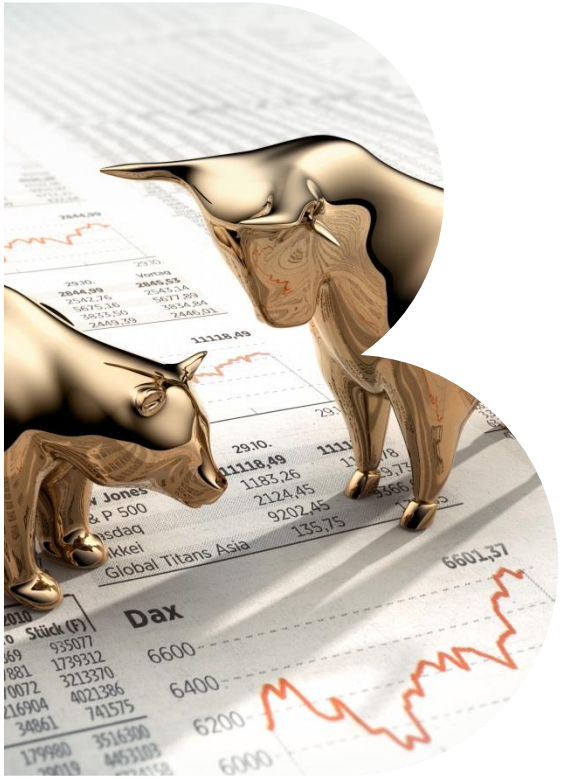
AM system | Ancillary system

Source: Roland Berger

Comments

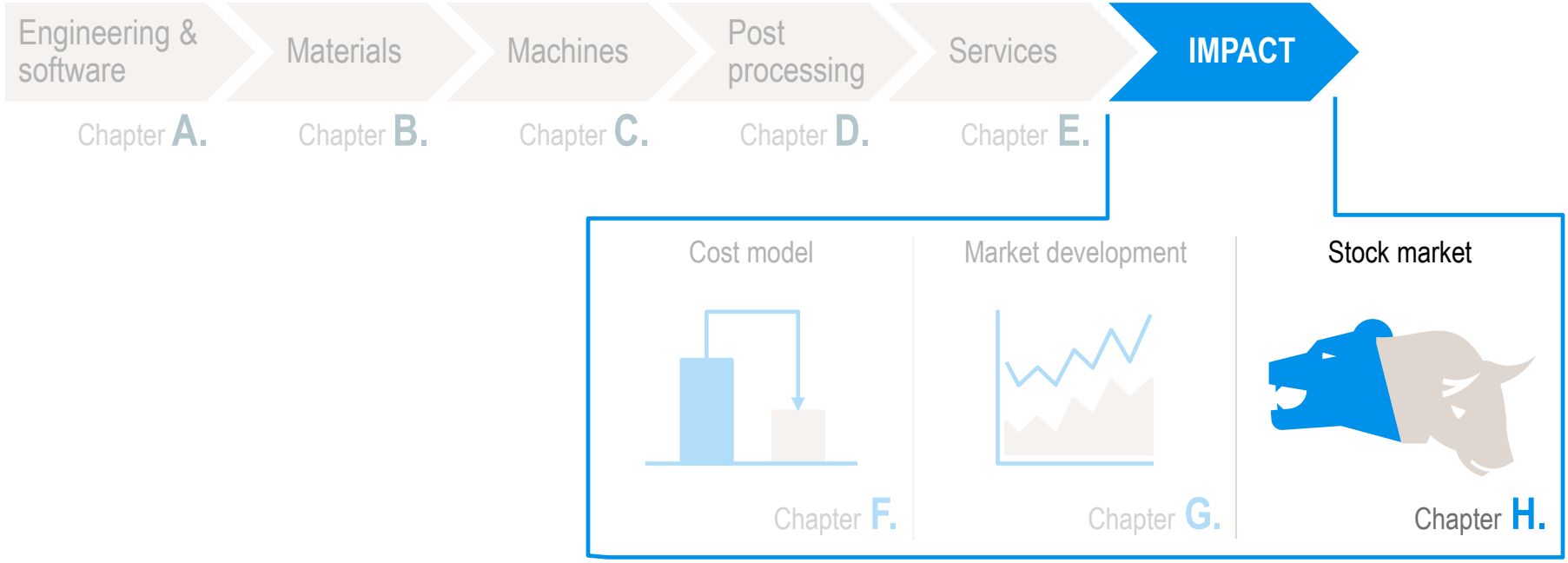
- Health risks stemming from the AM machine including laser system, inert gases and metal powder
  - Risks from metal powders require further examination
- **No guidelines available for powder handling** in industrial environments of 3D printing
- **No studies on health impact** from AM metal powders available
- **Several initiatives launched** in Germany to evaluate health impact of AM:
  - Institut für Arbeitsschutz der DGUV (IFA): "Gefahrstoffemissionen aus 3D-Druckern" (until end of 2018)
  - Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA): Project "3D Printer" (until 05/2017)
  - Verein Deutscher Ingenieure (VDI): Commision 105.6 "Safety during operation of AM machines"

H. Stock market



Additive Manufacturing – next generation (AMnx) is characterized by innovations along the entire AM process chain

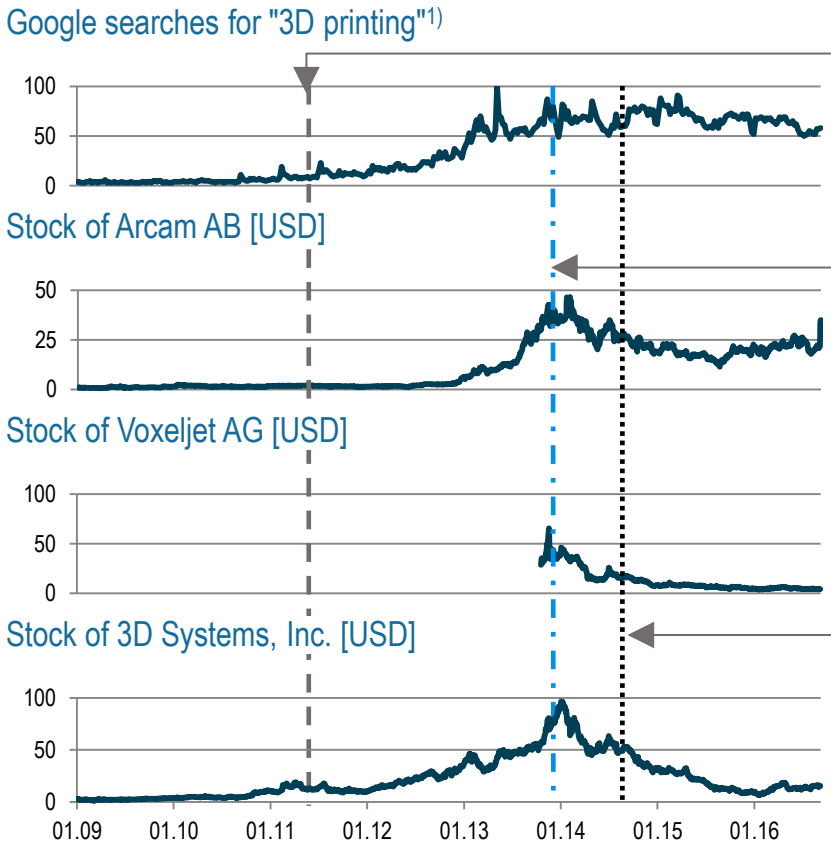
Next generation …



Source: Roland Berger

The first printed gun and the ensuing stock rally led to a media hype about Additive Manufacturing in 2013 and 2014

Key events in 3D printing



First major announcement of Additive Manufacturing

> GE starts industrial use of AM for its jet engines

Biggest hype

> 1st 3D printed gun is unveiled (May 3, 2013)

> News media all around the world start covering the 3D printing industry

Highest stock valuation

> IPO of the small German 3D printing company Voxeljet AG

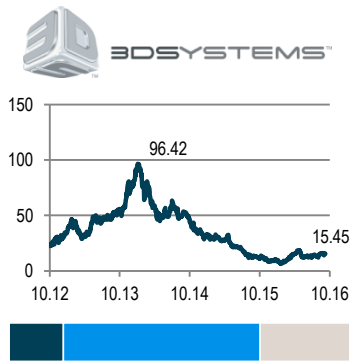
> Stock prices reach all-time high after five-month rally

1) Highest search volume = 100 points

Source: Bloomberg; Google Trends; Roland Berger

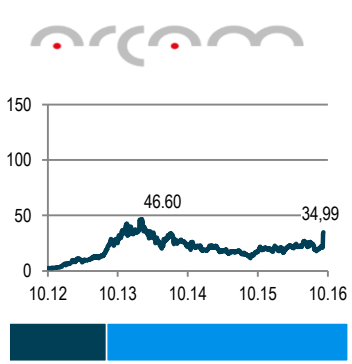
Although stock prices of established AM companies declined over the last years, analyst grades indicate hold or buy positions

Stock prices [USD]

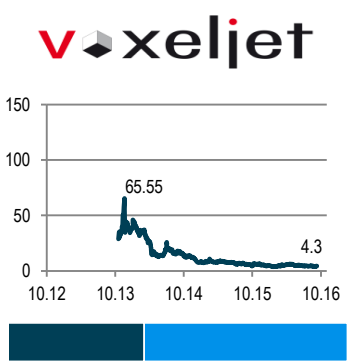


- IPO: 1989
- Focus on PBF (plastic)
- Daily trading volume since 2015 approx. 3.2 m stocks, tending upward
- 3D Systems is the AM pioneer – first system sold in 1988
- 52 acquisitions since 2009; cumulative acquisitions in 2014 total USD 345 m

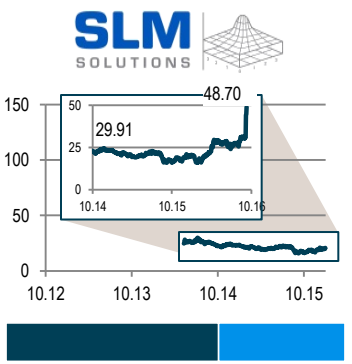
- IPO: 1994
- Focus on material extrusion
- Daily trading volume approx. 1.3 m stocks, tending upward
- Acquisition of MakerBot (2013) several service providers (2014) and RTC Rapid Tech (2015)
- New technology enables jetting of three different base materials



- IPO: 2000
- GE with bid on Arcam 09/2016
- Focus on PBF by electron beam
- Daily trading volume approx. 122 k stocks, tending upward
- Inventor of PBF by electron beam
- Expanded into powder materials and services
- 2 acquisitions in 2014 for USD 47 m



- IPO: 2013
- Focus on binder jetting
- Daily trading volume approx. 1.7 k stocks, stable tendency
- Developed new phenolic binder in 2014 enabling higher resolution, precision and powder recyclability rate
- Opened new service facility in the US in 2015



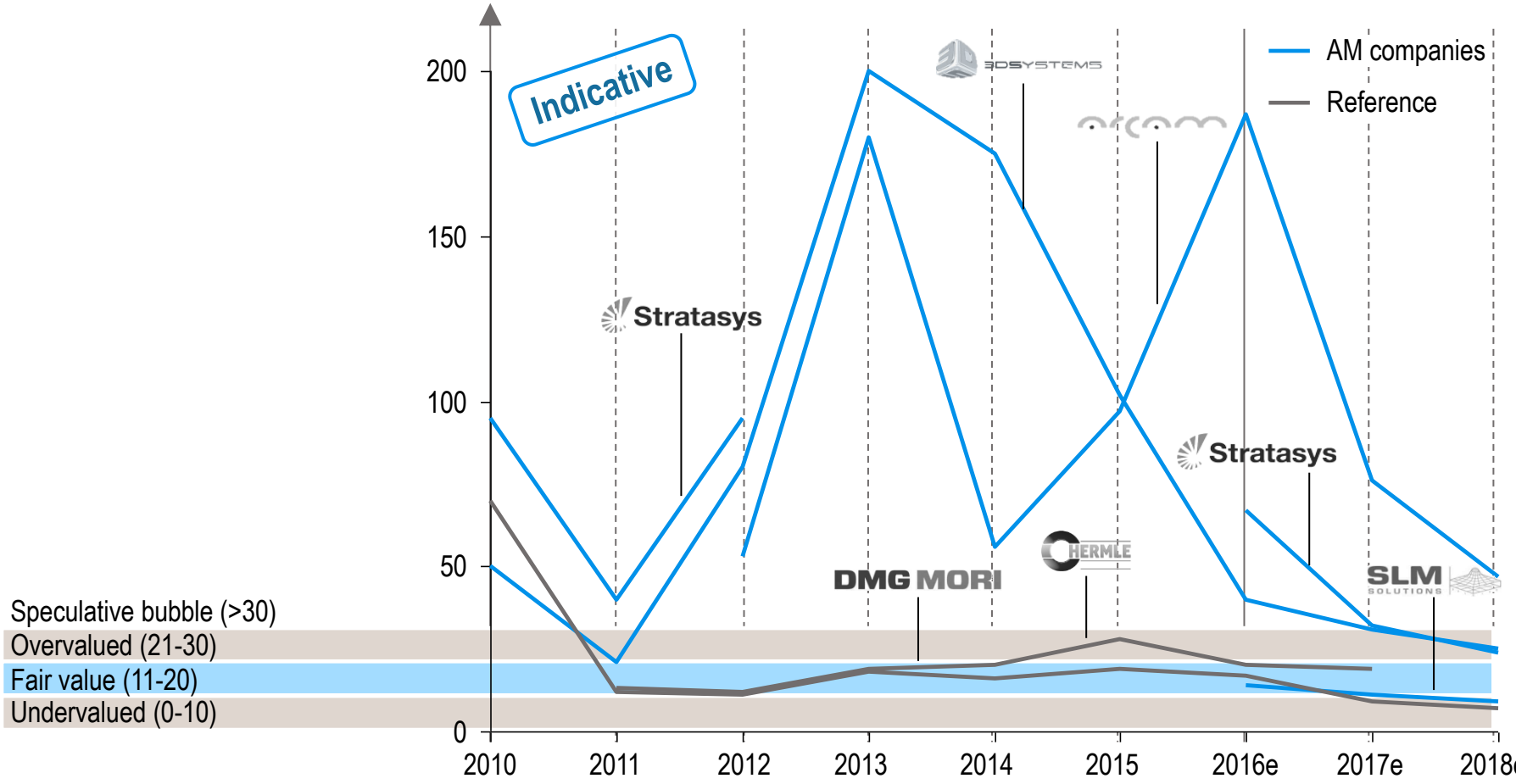
- IPO: 2014
- GE with bid on SLM Solutions 09/2016
- Focus on PBF by laser (metal)
- Daily trading volume approx. 42 k stocks, tending slightly upward
- Versatile systems due to open system architecture – most metal powders applicable

Analyst grades distribution: Buy Hold Sell

Source: Bloomberg; Broker Reports; Nasdaq; Yahoo Finance; Roland Berger

Overvalued AM stocks are approaching fair valuation – Stock profits are likely to be appropriate and stable in the medium term

Price/earnings ratios of listed AM suppliers



Source: Bloomberg; Capital IQ; Nasdaq; Roland Berger

Please contact us if you have any further questions

Dr. Bernhard Langefeld

Partner Engineered Products/High Tech

OpernTurm, Bockenheimer Landstraße 2-8

D-60306 Frankfurt

Tel.: +49 160 744 6143

bernhard.langefeld@rolandberger.com

Source: Roland Berger

Disclaimer

The study at hand was created by Roland Berger.

Roland Berger, founded in 1967, is the only leading global consultancy of German heritage and European origin. With 2,400 employees working in 36 countries, we have successful operations in all major international markets. Our 50 offices are located in the key global business hubs. Roland Berger advises major international industry and service companies as well as public institutions. Our services cover the entire range of management consulting from strategic advice to successful implementation.

The study at hand was particularly created for the benefit of the recipient and is based on certain assumptions and information available at the publishing date. Roland Berger does not give an express or implied warranty regarding the correctness and completeness of the information contained in this study. There is no guarantee that the included projections or estimates will be realized. No indication or statement in this study shall be understood as an assured prediction. Information provided by collaborating companies and research institutes has not been verified by Roland Berger. The reader should not act on any information provided in this study without receiving specific professional advice.

In publishing this study, Roland Berger reserves the right to make any necessary amendment or substitution and is not obliged to give the recipient access to the additional information.

Any other use or disclosure of this study to a third party is strictly prohibited, unless expressly permitted via written consent from Roland Berger. The image rights remain with the respective originator at any time.

Roland Berger shall not be liable for any damages resulting from the use of information contained in the study.


Roland
Berger