UNIVERSIDADE DE SÃO PAULO

ESCOLA DE ENGENHARIA DE SÃO CARLOS

DEPARTAMENTO DE ENGENHARIA DE PRODUÇÃO

SEP 0605 – Automação da Produção

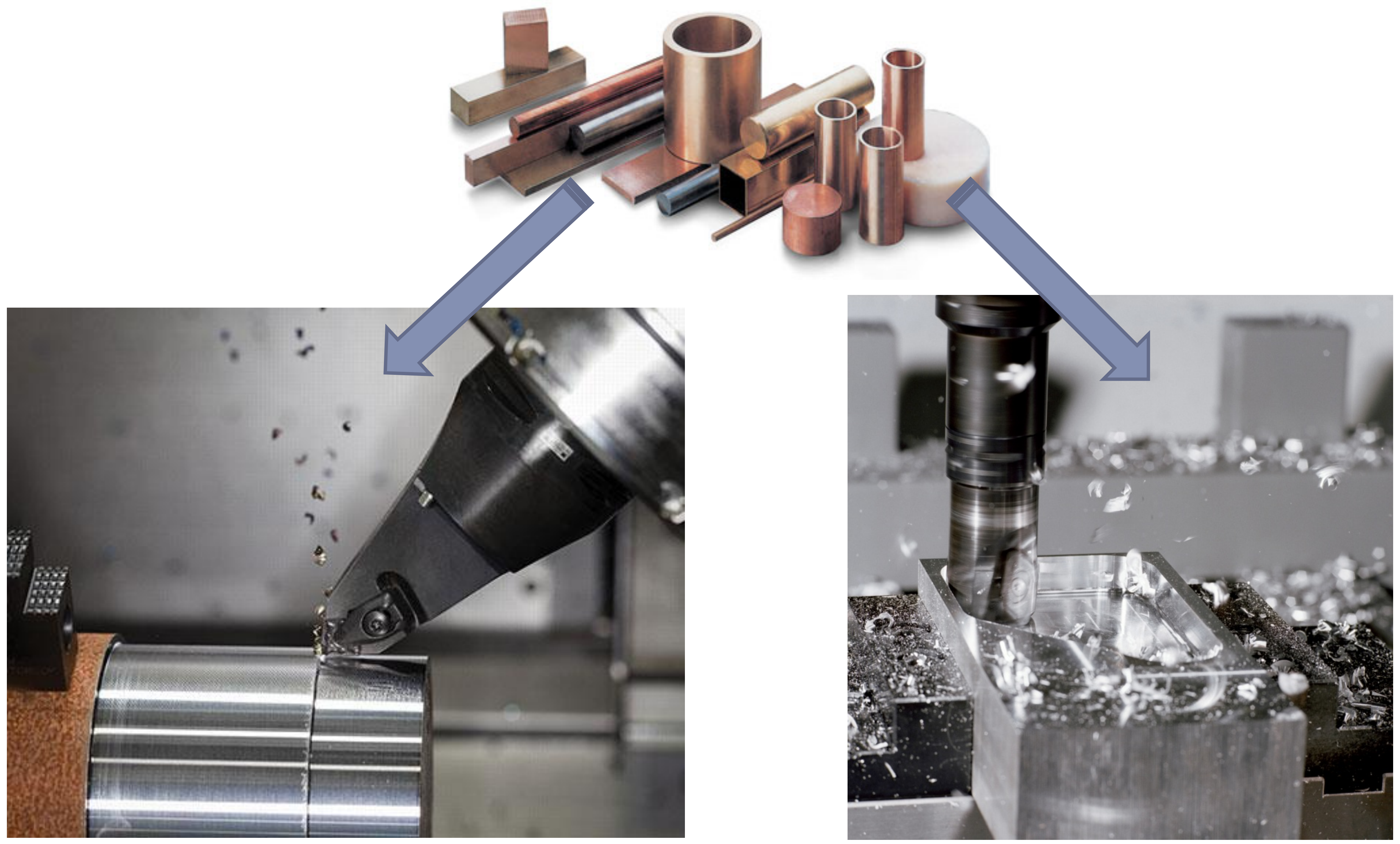
Aula 7 – Manufatura aditiva

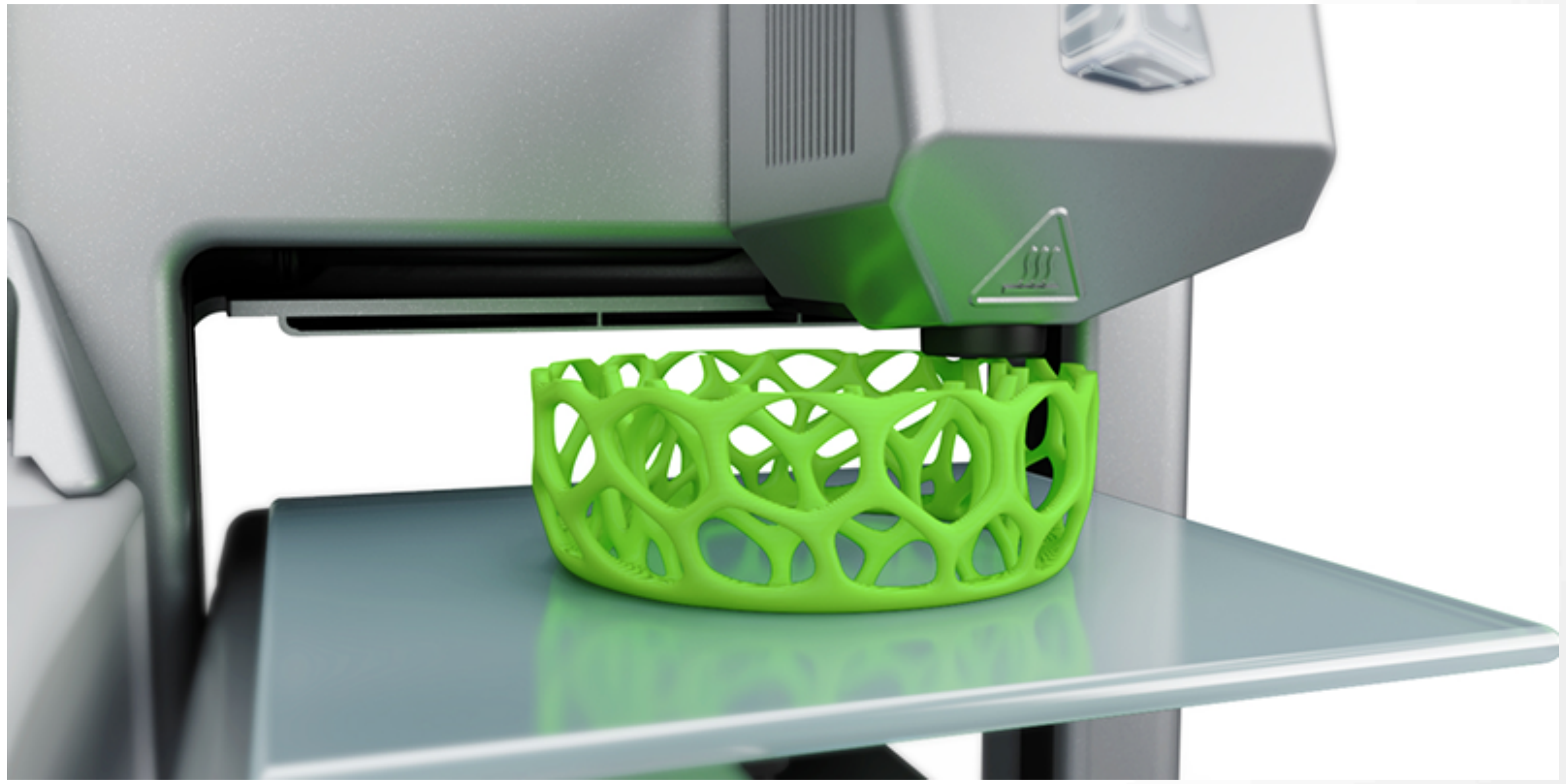
Prof. Eraldo Jannone da Silva

1. Fundamentos da manufatura aditiva

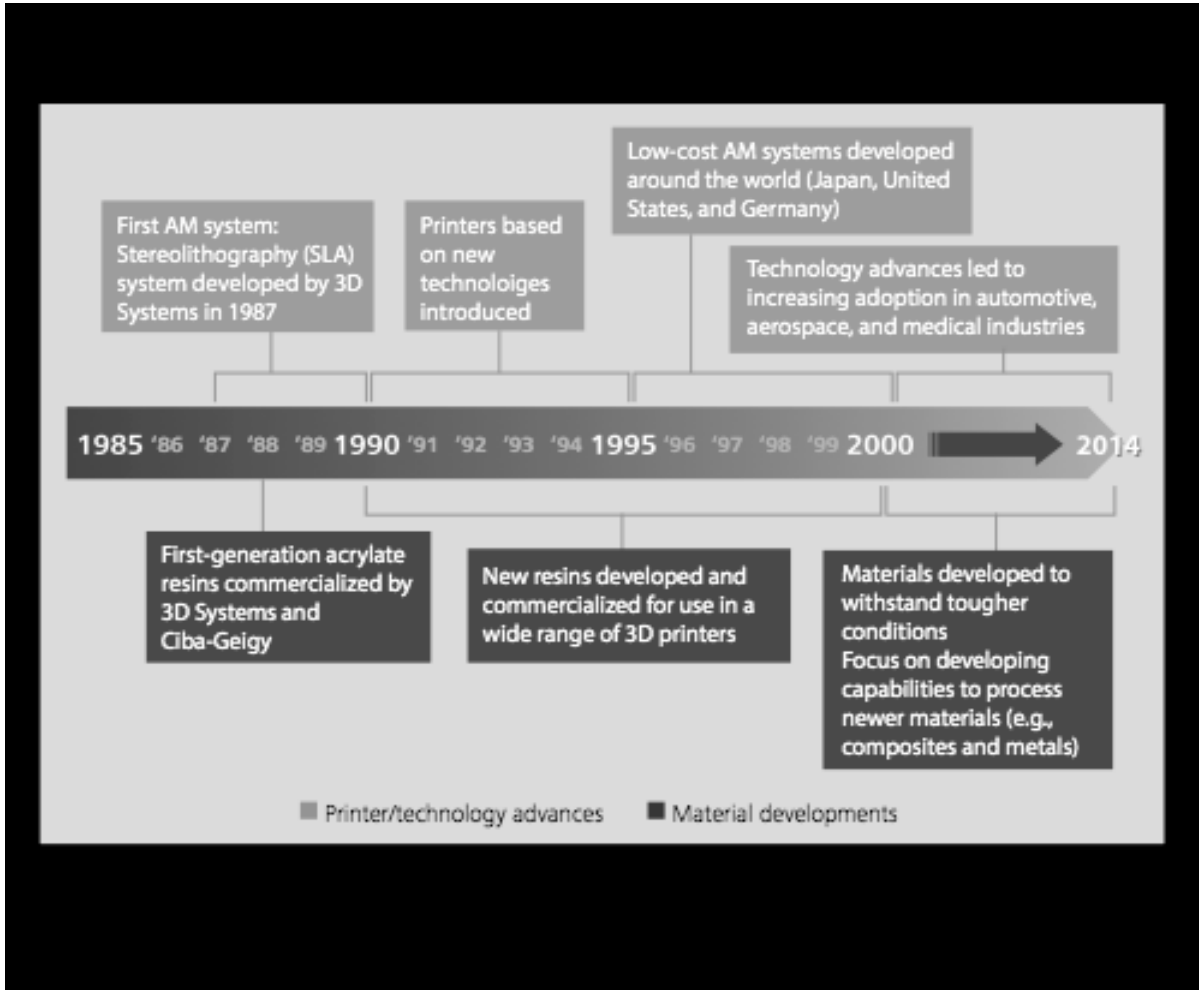
Manufatura tradicional - subtrativa

Manufatura aditiva



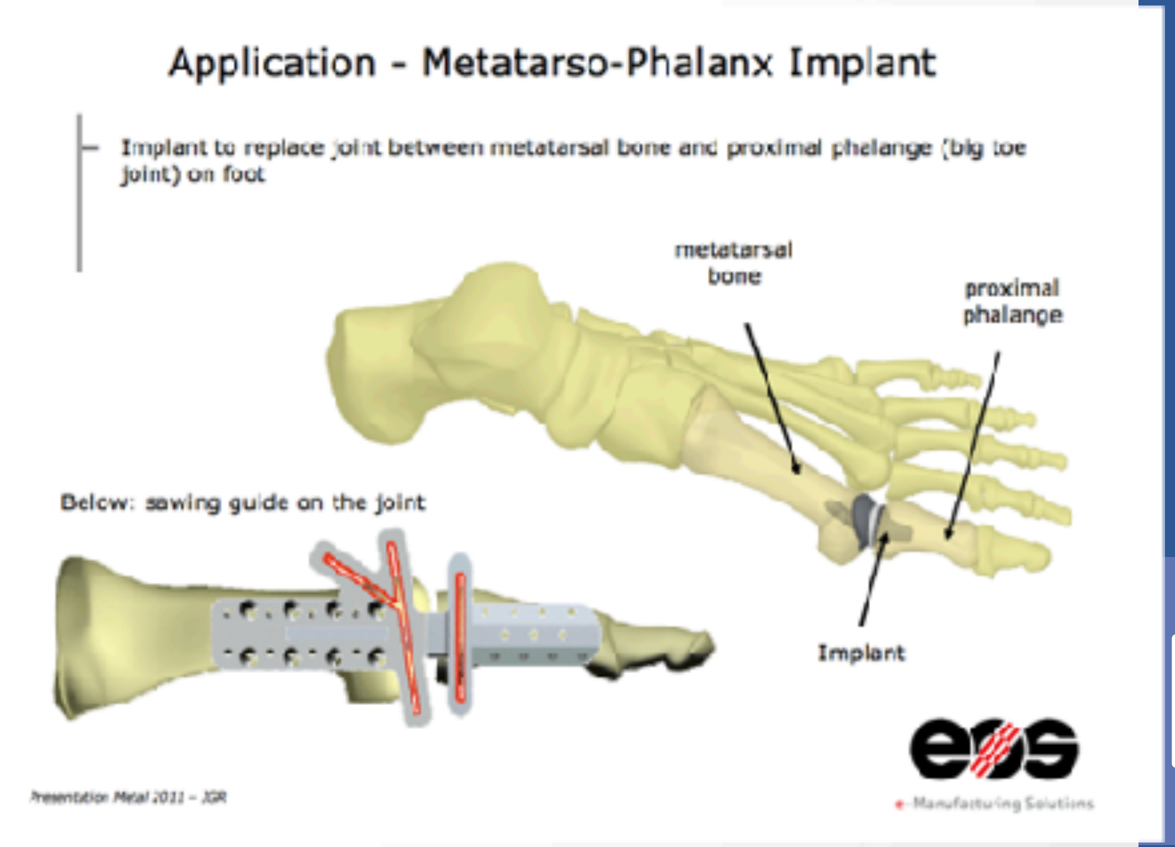


1. Fundamentos da manufatura aditiva



Fonte: Delloite University Press

Fonte: 3D printing - https://3dprint.com/119885/wake-forest-3d-printed-tissue/



1. Fundamentos da manufatura aditiva

Perspectivas futuras

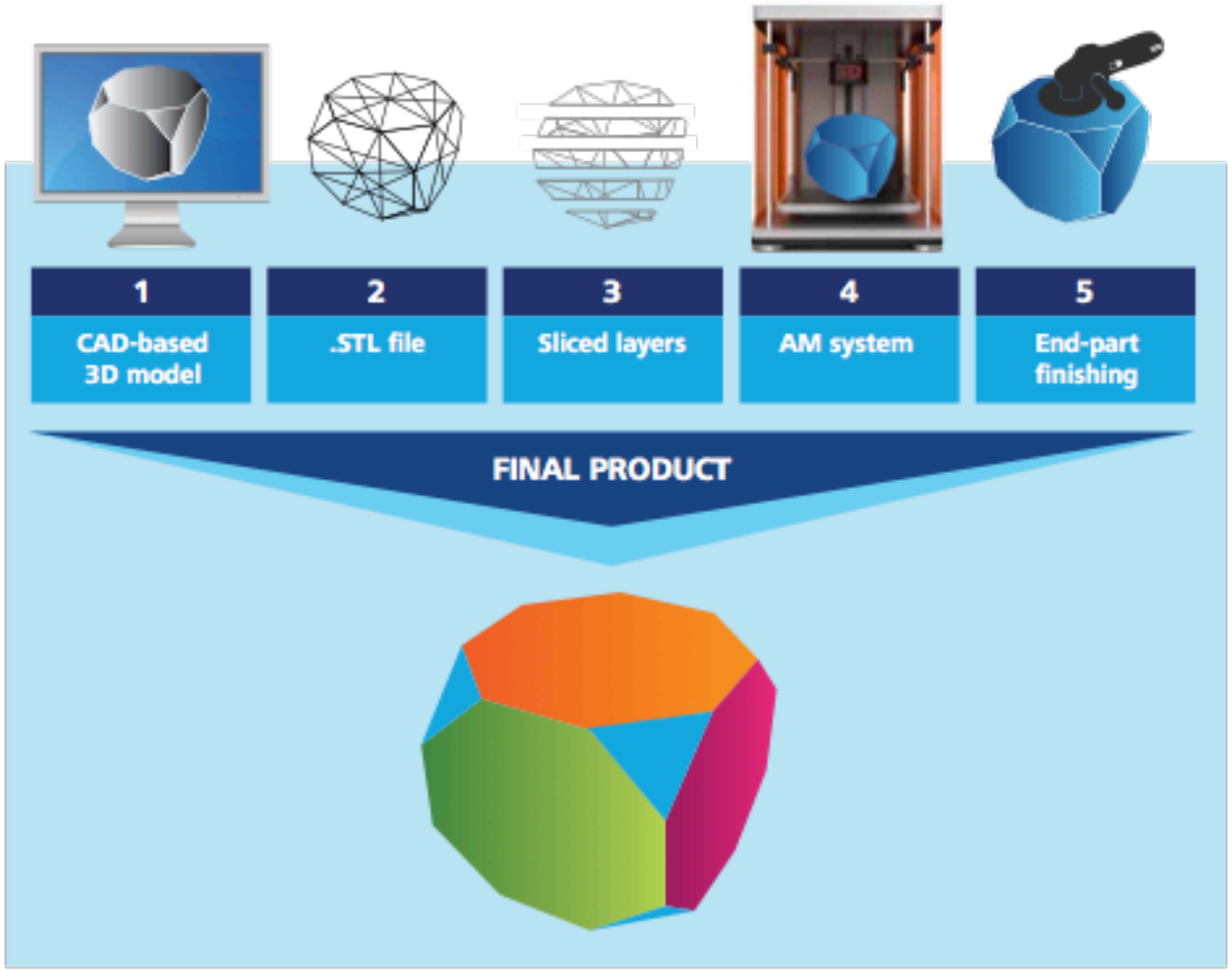
3D Printing 2015 Ford Mustang in Chocolate

http://3dprinting.com/food/

Post-processed and polished cufflinks made of 18 ct yellow gold, designed by Digital Forming (Source: CPM).

1. Fundamentos da manufatura aditiva

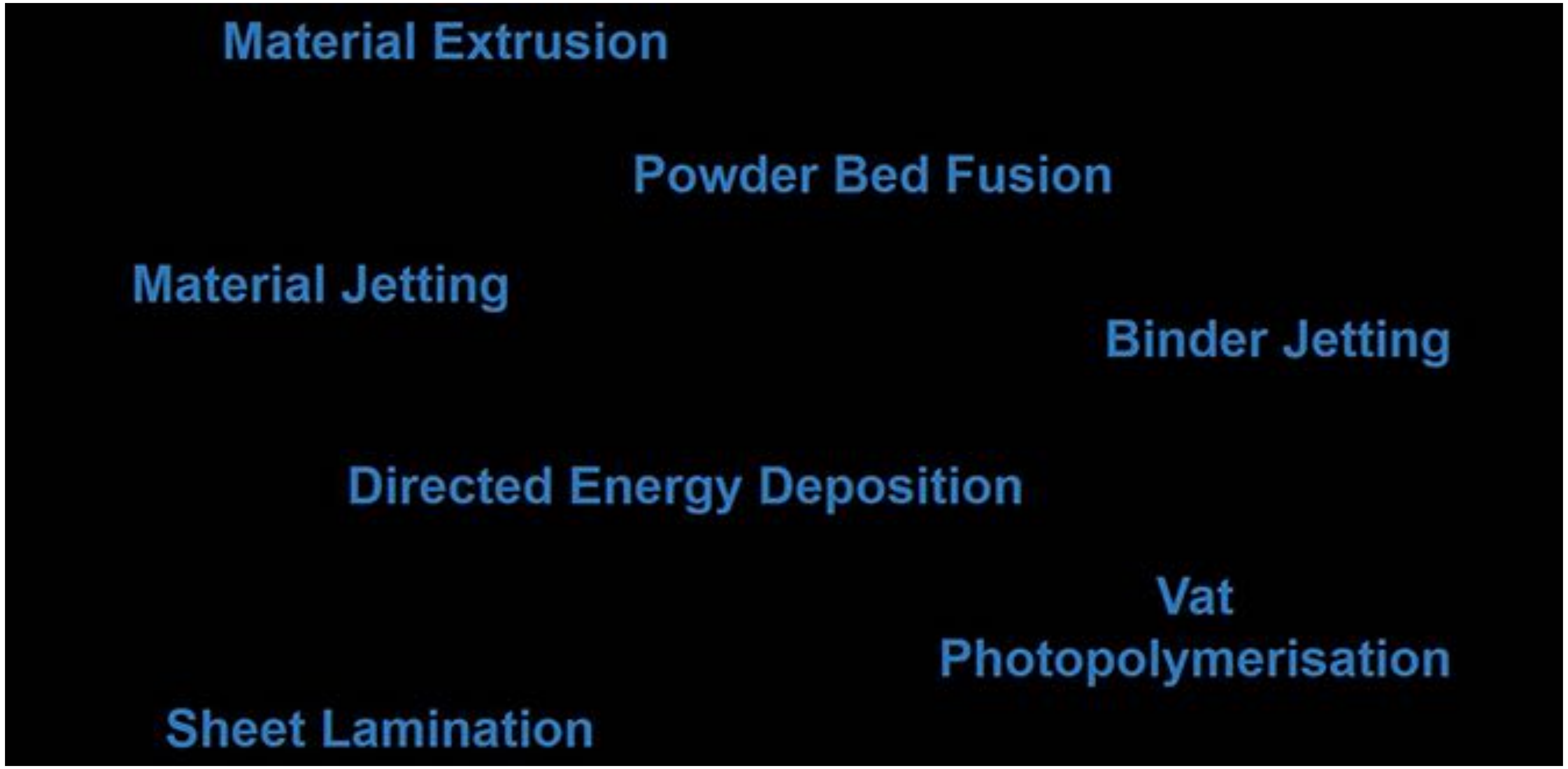
Figure 2. Additive manufacturing (AM) process flow



Graphic: Deloitte University Press | DUPress.com

Fonte: Delloite University Press

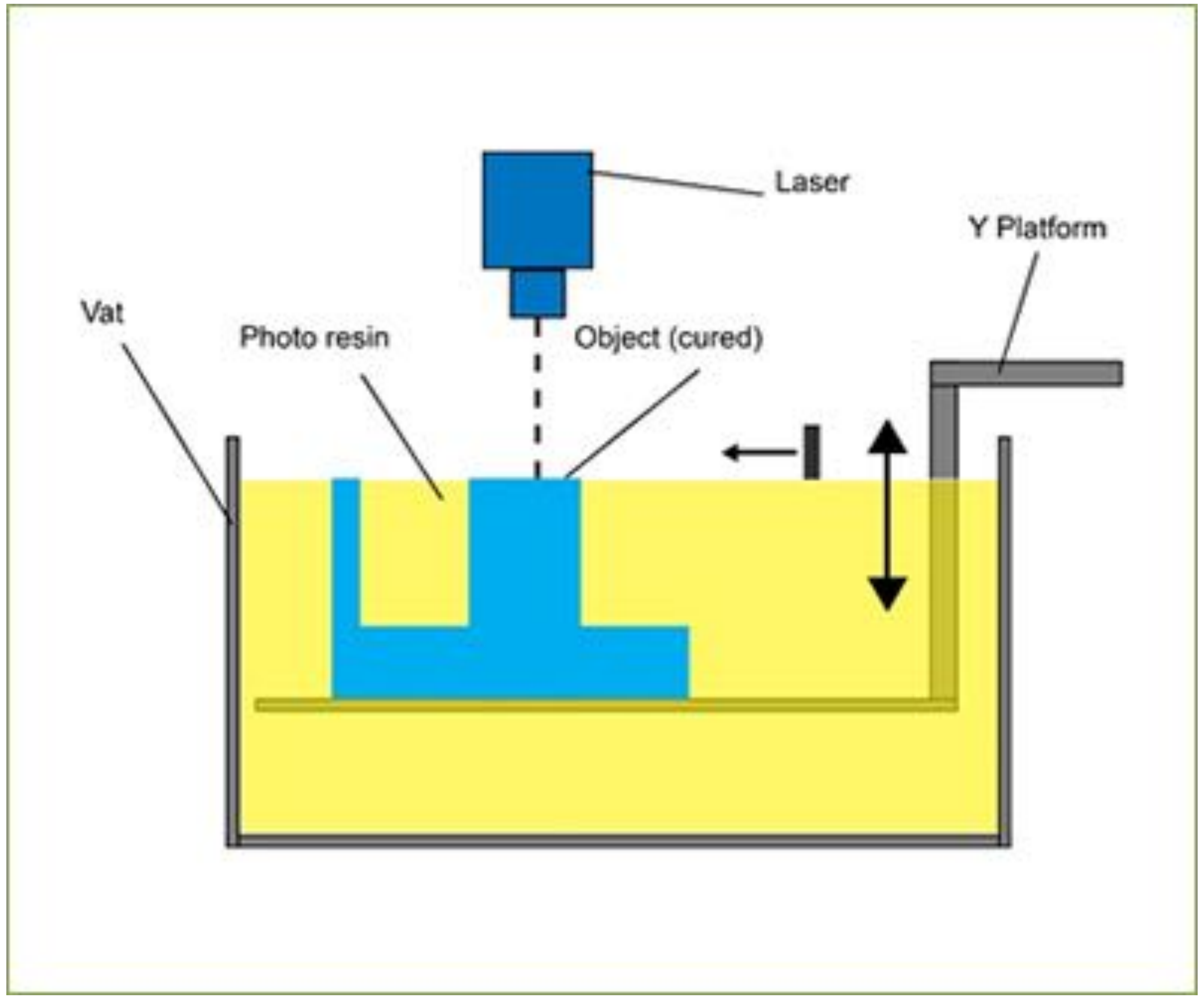
1. Fundamentos da manufatura aditiva



Fonte: Additive Manufacturing Research Group – Loughborough University
http://www.lboro.ac.uk/research/amrg/about/
the7categoriesofadditivemanufacturing/

SEP 0605 - Automação da Produção

1.1 Tecnologias LASER



https://youtu.be/oNpAnBhgIIs

Fonte: Additive Manufacturing Research Group – Loughborough University - http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/vatphotopolymerisation/

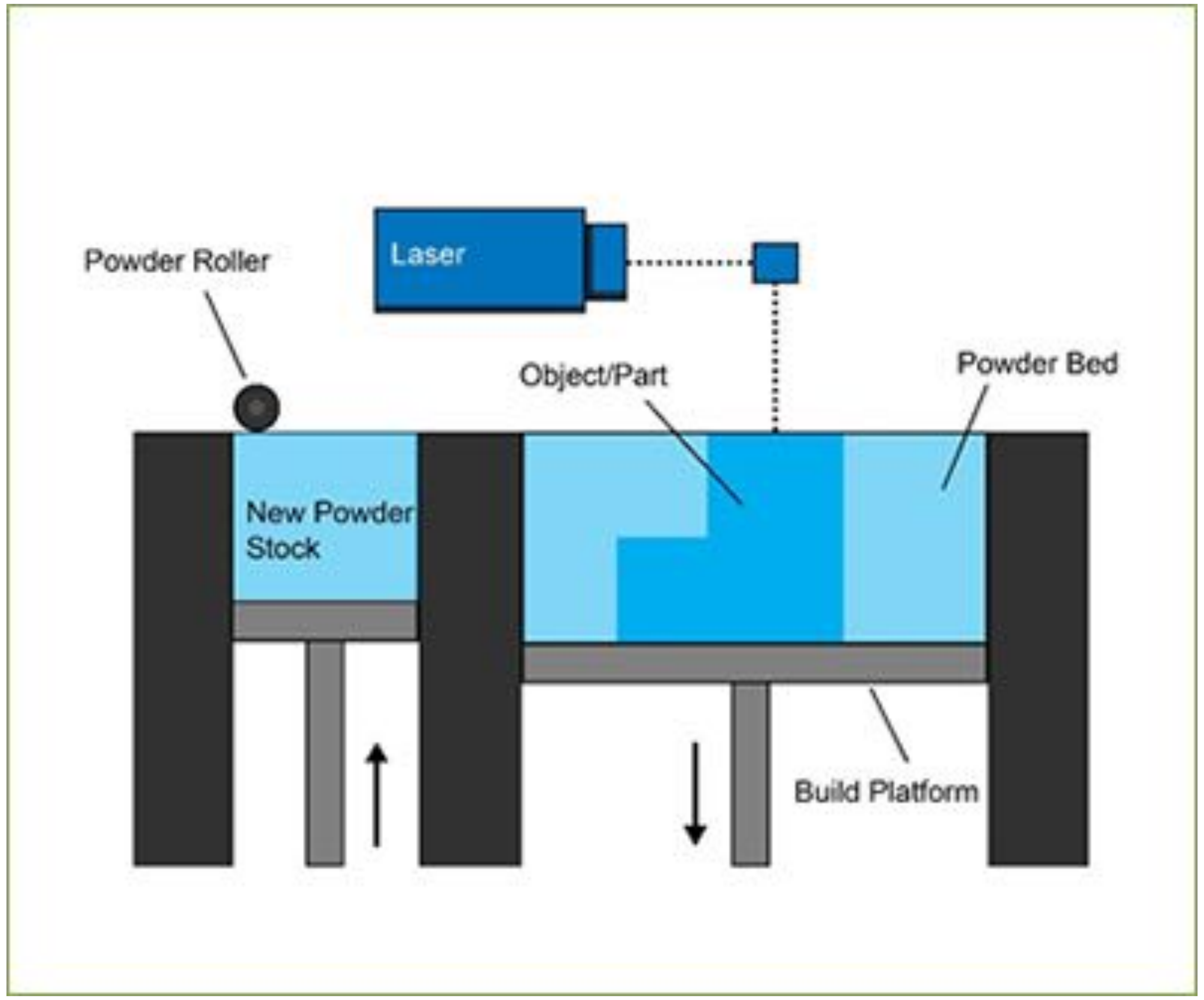
Vat photopolymerization

In vat photopolymerization, a liquid photopolymer (i.e., plastic) in a vat is selectively cured by light-activated polymerization. The process is also referred to as light polymerization.

Related AM technologies: Stereolithography (SLA), digital light processing (DLP)

Fonte: Delloite University Press

1.2 Tecnologias LASER



Fonte: Additive Manufacturing Research Group – Loughborough University
http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/

https://youtu.be/oO77VKDB89I

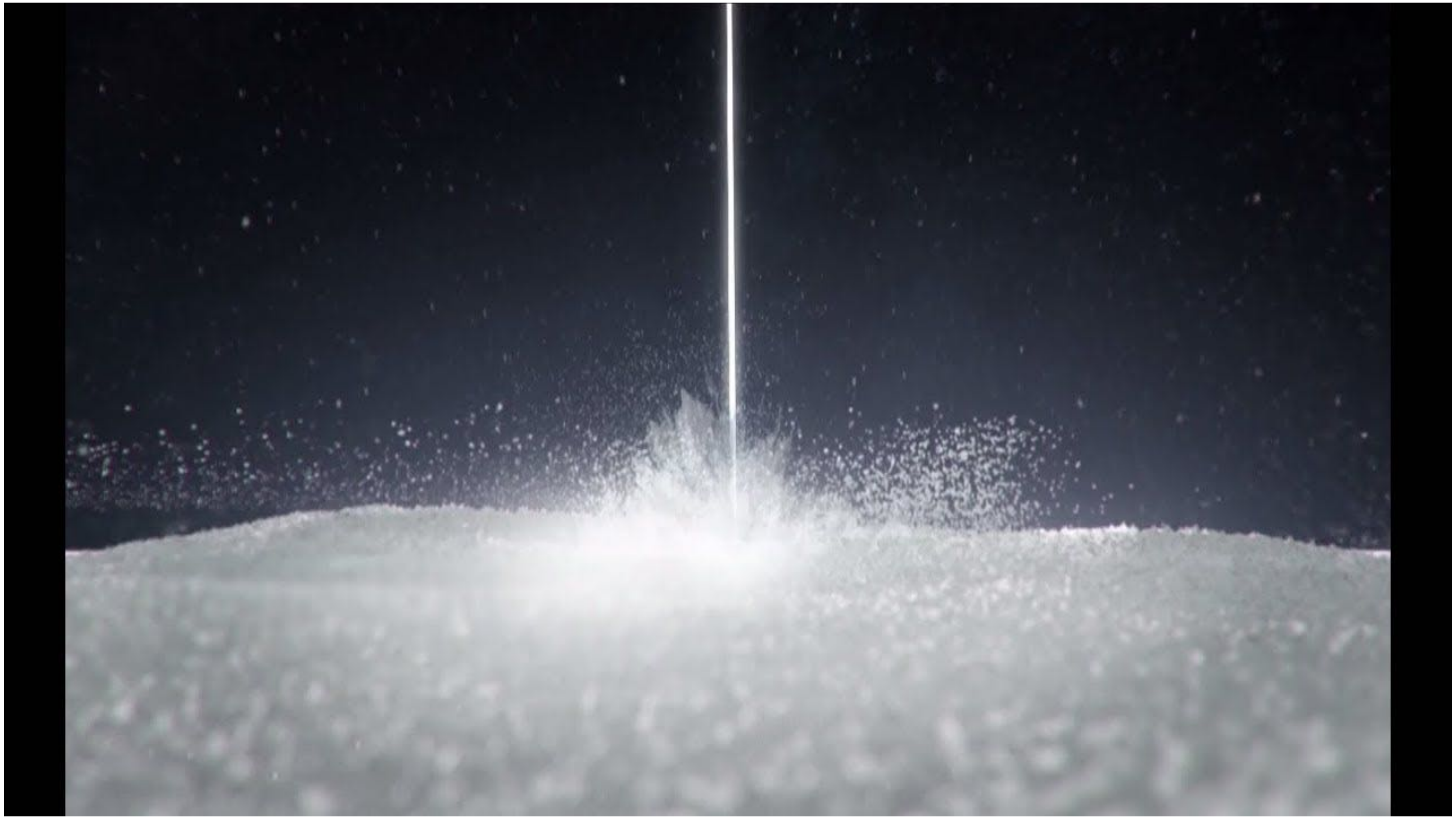
Powder bed fusion

In powder bed fusion, particles of material (e.g., plastic, metal) are selectively fused together using a thermal energy source such as a laser. Once a layer is fused, a new one is created by spreading powder over the top of the object and repeating the process. Unfused material is used to support the object being produced, thus reducing the need for support systems.

Related AM technologies: Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)

Fonte: Delloite University Press

1.2 Tecnologias LASER

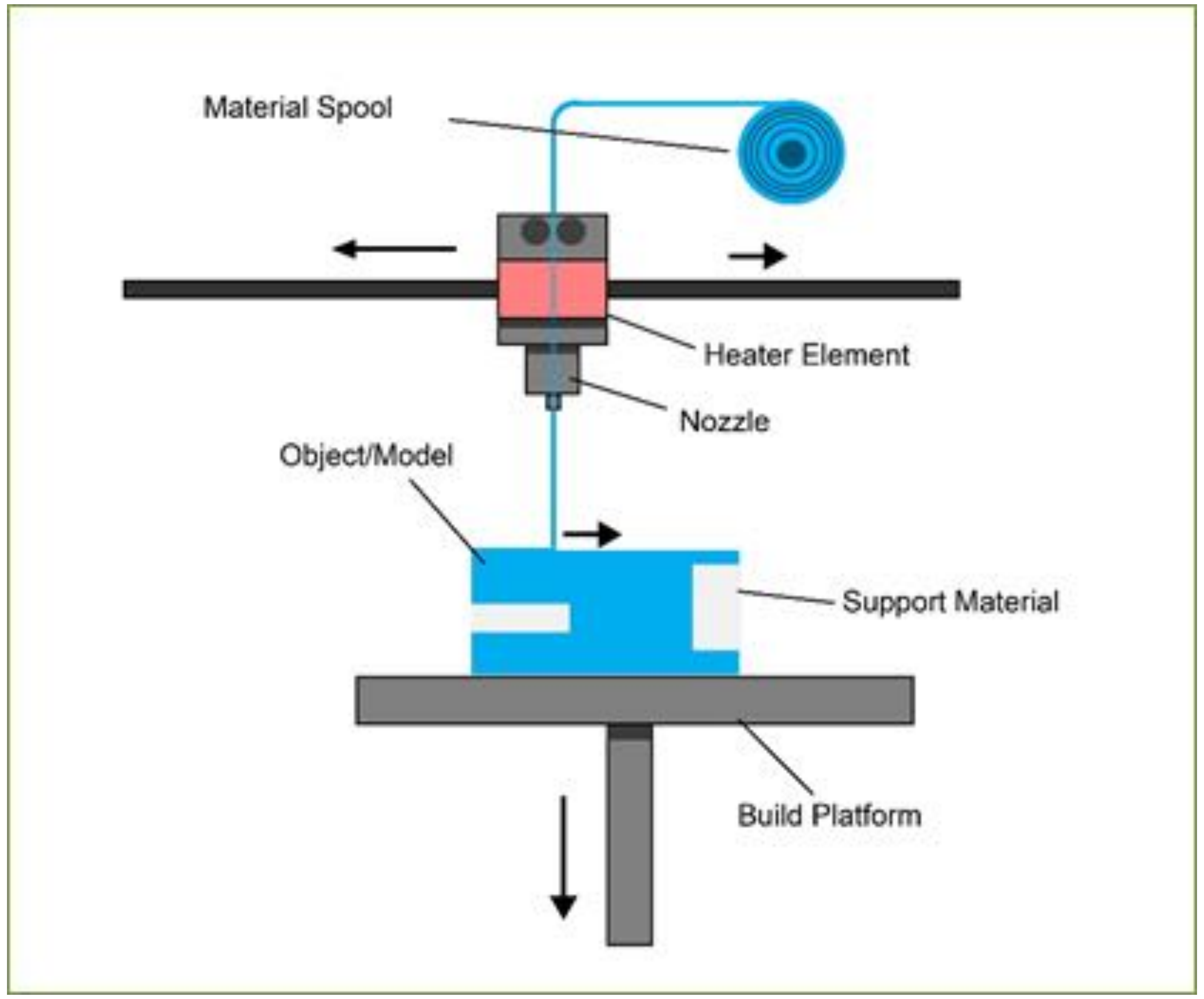


Fonte: EOS https://www.youtube.com/watch?v=O6ChlcBBmj4

1.2 Tecnologias LASER

Fonte: TiMortar https://www.youtube.com/watch?v=Y-dTc8_3dU0

1.3 Tecnologias de extrusão



https://youtu.be/J4OQQ9bA6g0

Fonte: Additive Manufacturing Research Group – Loughborough University http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/

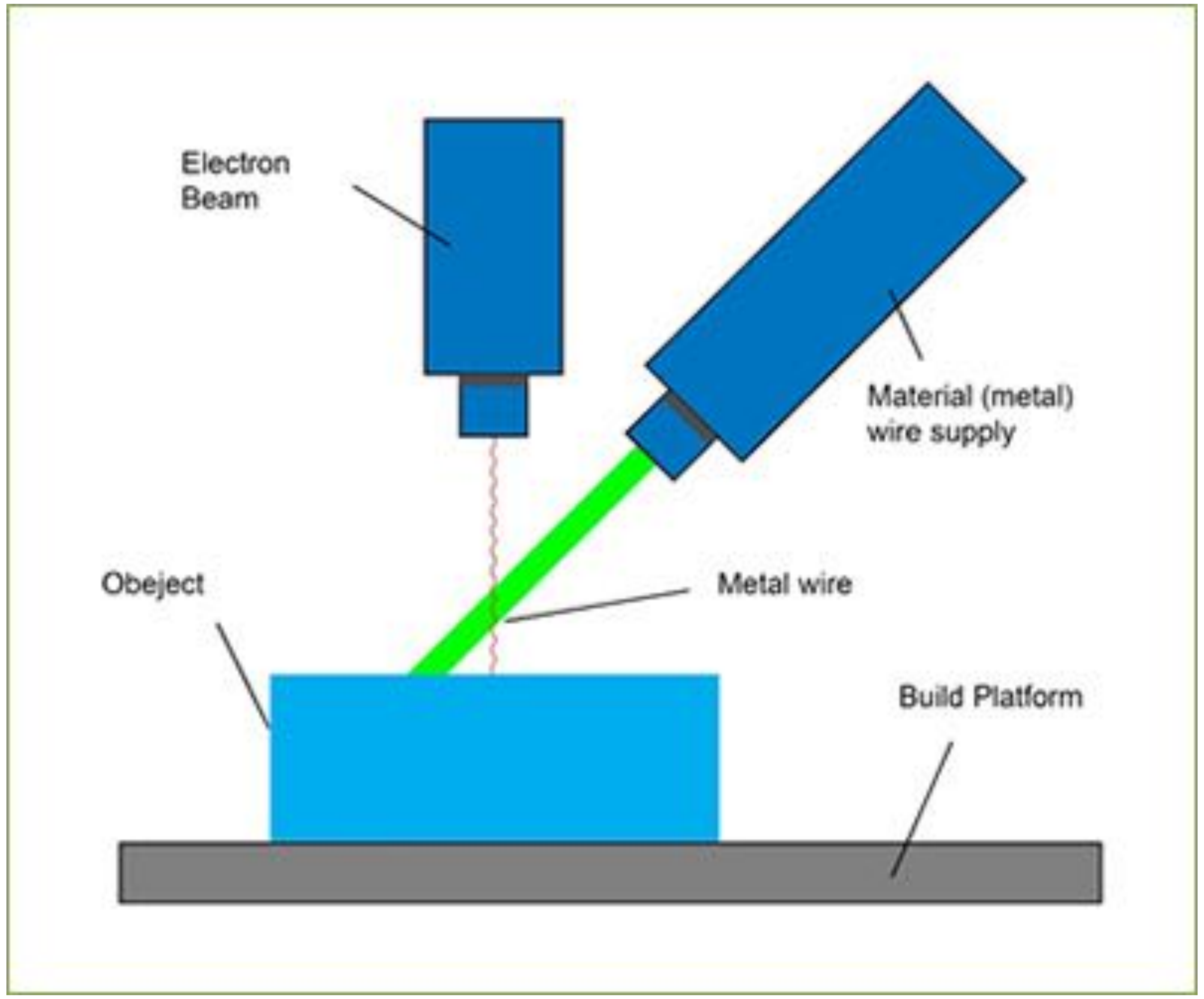
Material extrusion

In material extrusion, thermoplastic material is fed through a heated nozzle and deposited on a build platform. The nozzle melts the material and extrudes it to form each object layer. This process continues until the part is completed.

Related AM technologies: Fused deposition modeling (FDM)

Fonte: Delloite University Press

1.3 Tecnologias de extrusão



Fonte: Additive Manufacturing Research Group – Loughborough University
http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/

https://www.youtube.com/watch?v=Pjqysyy1ySs

https://www.youtube.com/watch?v=ylMftRD5DhU

Directed energy deposition

In directed energy deposition, focused thermal energy is used to fuse (typically metal) material as it is being deposited. Directed energy deposition systems may employ either wire-based or powder-based approaches.

Related AM technologies: Laser metal deposition (LMD)

Fonte: Delloite University Press

1.3 Tecnologias de extrusão

Directed energy deposition
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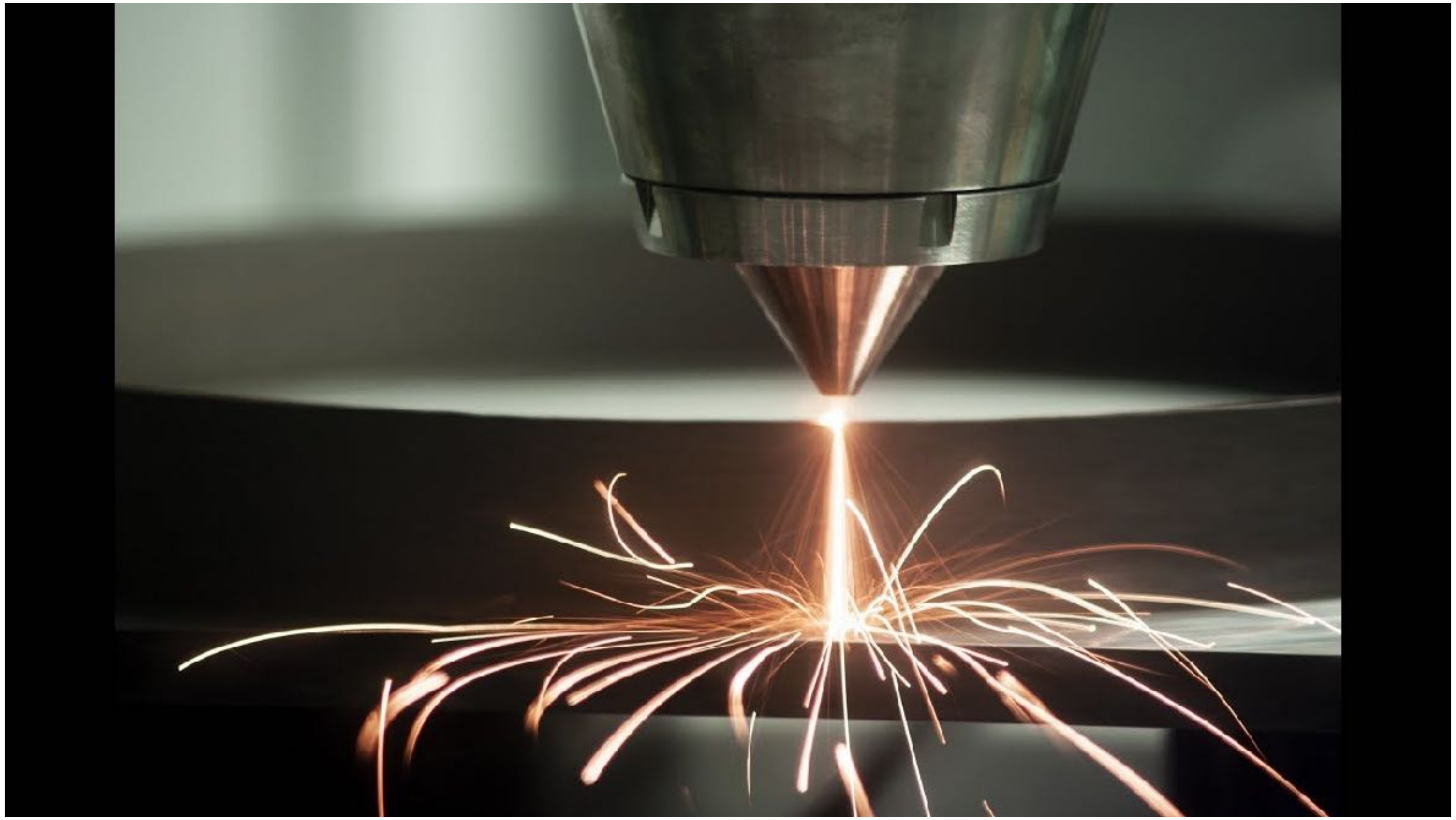

Fonte: BeAM - https://www.youtube.com/watch?v=oL7bMhPTtDI

1.3 Tecnologias de extrusão

Directed energy deposition
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Related AM technologies: Laser metal deposition (LMD)

Fonte: Romi - https://www.youtube.com/watch?v=2OQ2HUPlMHU

Fonte: Romi - https://www.youtube.com/watch?v=nD9mrJ5Tx6Q&t=22s

1.3 Tecnologias de extrusão

Directed energy deposition

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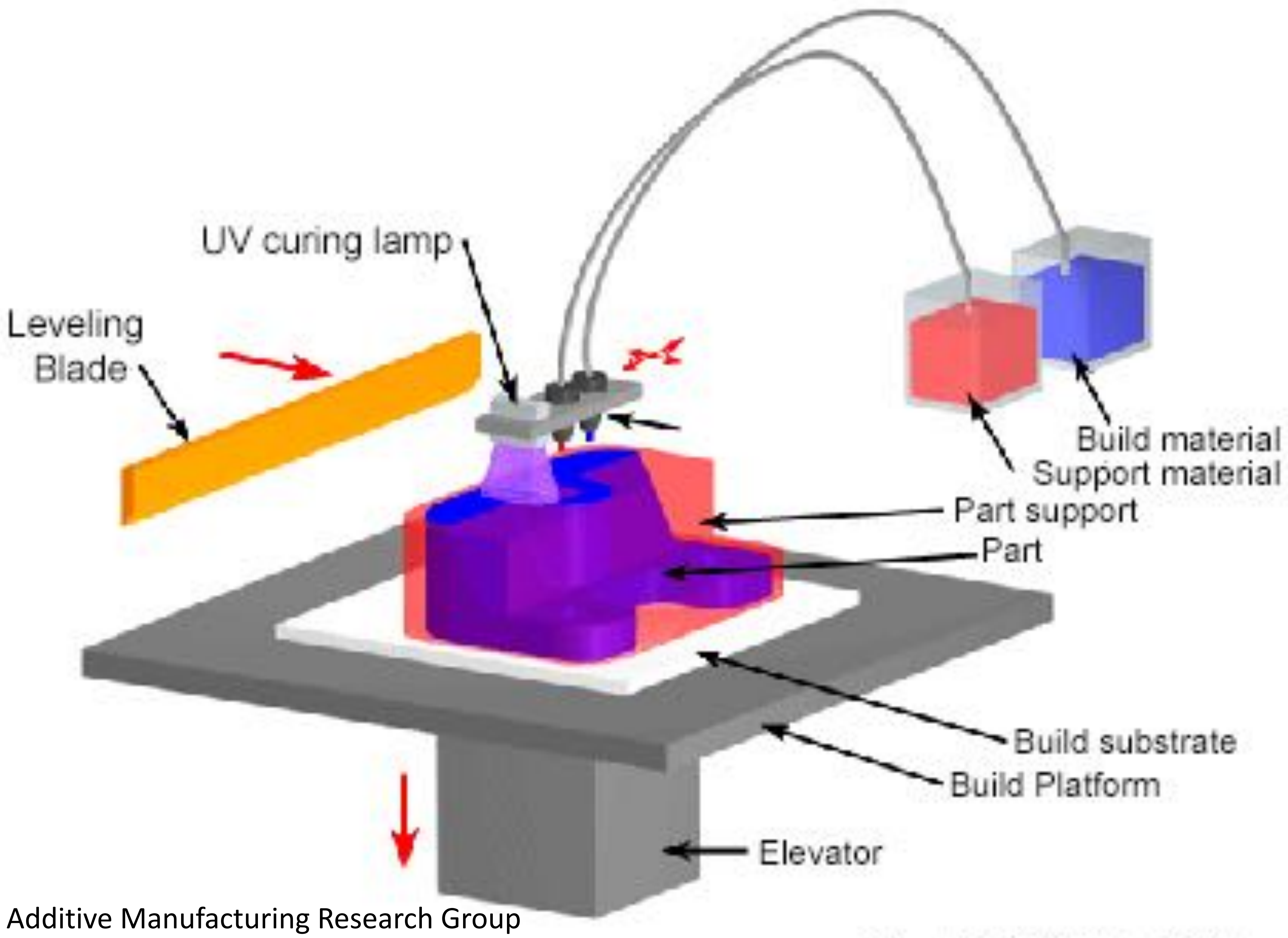
Fonte: Romi -https://www.youtube.com/watch?v=fqmD9REdPJg

1.4 Tecnologias de jato



Fonte: Additive Manufacturing Research Group – Loughborough University http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/

https://www.youtube.com/watch?v=oi0JEhGqTuU

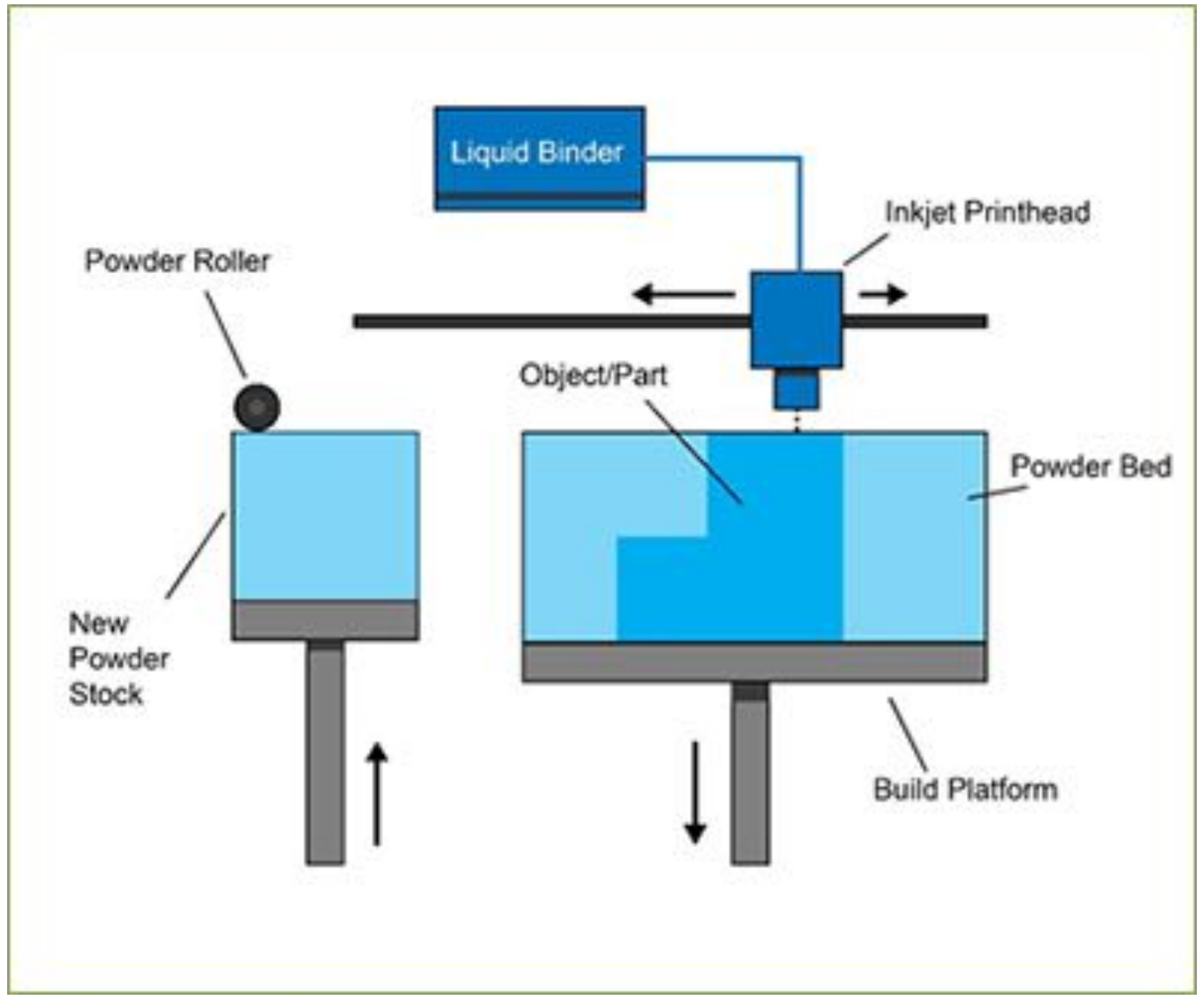
Material jetting

In material jetting, a print head selectively deposits material on the build area. These droplets are most often comprised of photopolymers with secondary materials (e.g., wax) used to create support structures during the build process. A UV light solidifies the photopolymer material to form cured parts. Support material is removed during post-build processing.

Related AM technologies: Multi-jet modeling (MJM)

Fonte: Delloite University Press

1.4 Tecnologias de jato



https://youtu.be/ONMYx1yhJuo

Fonte: Additive Manufacturing Research Group – Loughborough University http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/

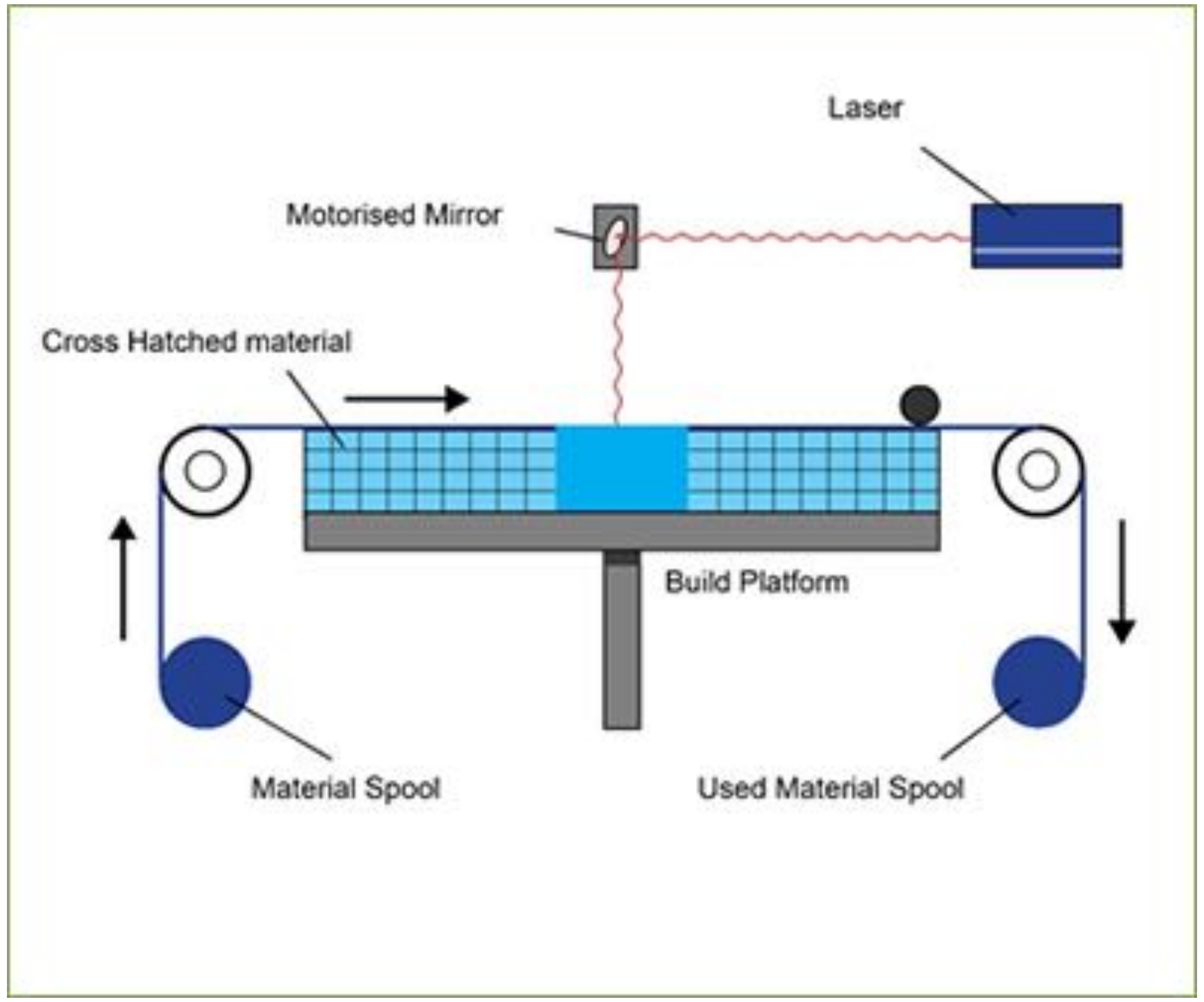
Binder jetting

In binder jetting, particles of material are selectively joined together using a liquid binding agent (e.g., glue). Inks may also be deposited in order to impart color. Once a layer is formed, a new one is created by spreading powder over the top of the object and repeating the process. This process is repeated until the object is formed. Unbound material is used to support the object being produced, thus reducing the need for support systems.

Related AM technologies: Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)

Fonte: Delloite University Press

1.5. Tecnologias de laminação



https://www.youtube.com/watch?v=GUvnz0borAI&t=30s

"Laminated object manufacturing (LOM). Laminated object manufacturing (LOM) uses a similar layer by layer approach but uses paper as material and adhesive instead of welding. The LOM process uses a cross hatching method during the printing process to allow for easy removal post build. Laminated objects are often used for aesthetic and visual models and are not suitable for structural use."

Fonte: Additive Manufacturing Research Group – Loughborough University
http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/

Sheet lamination

In sheet lamination, thin sheets of material (e.g., plastic or metal) are bonded together using a variety of methods (e.g., glue, ultrasonic welding) in order to form an object. Each new sheet of material is placed over previous layers. A laser or knife is used to cut a border around the desired part and unneeded material is removed. This process is repeated until the part is completed.

Related AM technologies: Laminated object manufacturing (LOM), ultrasonic consolidation (UC)

Fonte: Delloite University Press

1.6 Fundamentos da manufatura aditiva - Quadro resumo

Figure 4. AM technologies, corresponding base materials, and advantages and disadvantages

Technology	AM process	Typical materials	Advantages	Disadvantages
Stereolithography https://youtu.be/oNpAnBhgIIs	Vat polymerization	Liquid photopolymer, composites	Complex geometries; detailed parts; smooth finish	Post-curing required; requires support structures
Digital light processing	Vat polymerization	Liquid photopolymer	Allows concurrent production; complex shapes and sizes; high precision	Limited product thickness; limited range of materials
Multi-jet modeling (MJM) https://www.youtube.com/watch?v=oi0JEhGqTuU	Material jetting	Photopolymers, wax	Good accuracy and surface finish; may use multiple materials (also with color); hands-free removal of support material	Range of wax-like materials is limited; relatively slow build process
Fused deposition modeling https://youtu.be/J4OQQ9bA6g0	Material extrusion	Thermoplastics	Strong parts; complex geometries	Poorer surface finish and slower build times than SLA
Electron beam melting	Powder bed fusion	Titanium powder, cobalt chrome	Speed; less distortion of parts; less material wastage	Needs finishing; difficult to clean the machine; caution required when dealing with X-rays
Selective laser sintering https://youtu.be/oO77VKDB89I	Powder bed fusion	Paper, plastic, metal, glass, ceramic, composites	Requires no support structures; high heat and chemical resistant; high speed	Accuracy limited to powder particle size; rough surface finish
Selective heat sintering	Powder bed fusion	Thermoplastic powder	Lower cost than SLS; complex geometries; no support structures required; quick turnaround	New technology with limited track record
Direct metal laser sintering	Powder bed fusion	Stainless steel, cobalt chrome, nickel alloy	Dense components; intricate geometries	Needs finishing; not suitable for large parts
Powder bed and inkjet head printing	Binder jetting	Ceramic powders, metal laminates, acrylic, sand, composites	Full-color models; inexpensive; fast to build	Limited accuracy; poor surface finish
Plaster-based 3D printing	Binder jetting	Bonded plaster, plaster composites	Lower price; enables color printing; high speed; excess powder can be reused	Limited choice of materials; fragile parts
Laminated object manufacturing https://www.youtube.com/watch?v=GUvnz0borAI&t=30s	Sheet lamination	Paper, plastic, metal laminates, ceramics, composites	Relatively less expensive; no toxic materials; quick to make big parts	Less accurate; non-homogenous parts

Figure 4. AM technologies, corresponding base materials, and advantages and disadvantages (cont.)

Technology	AM process	Typical materials	Advantages	Disadvantages
Ultrasonic consolidation	Sheet lamination	Metal and metal alloys	Quick to make big parts; faster build speed of newer ultrasonic consolidation systems; generally non-toxic materials	Parts with relatively less accuracy and inconsistent quality compared to other AM processes; need for post-processing
Laser metal deposition https://youtu.be/oL7bMhPTtDI	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; ability to build large parts; production flexibility	Relatively higher cost of systems; support structures are required; need for post-processing activities to obtain smooth finish

Sources: Deloitte analysis; Wohlers Associates, *Additive manufacturing and 3D printing state of the industry*, 2012; Troy Jensen and Pipar Jaffray, *3D printing: A model of the future*, March 2013; Justin Scott, IDA Science and Technology Policy Institute, *Additive manufacturing: status and opportunities*, March 2012.

Graphic: Deloitte University Press | DUPress.com

Figure 5. Technologies and materials matrix[12]

Technology	Polymers	Metals	Ceramics	Composites
Stereolithography	●			●
Digital light processing	●			
Multi-jet modeling (MJM)	●			●
Fused deposition modeling	●			
Electron beam melting		●		
Selective laser sintering	●	●	●	●
Selective heat sintering	●			
Direct metal laser sintering		●		
Powder bed and inkjet head printing[13]	●	●	●	●
Plaster-based 3D printing			●	●
Laminated object manufacturing[14]	●	●	●	●
Ultrasonic consolidation		●		
Laser metal deposition		●		●

Sources: Deloitte analysis; Wohlers Associates, *Additive manufacturing and 3D printing state of the industry*, 2012; Phil Reeves, *3D printing & additive manufacturing: Extending your printing capability in true 3D*, Econolyst, June 12, 2012, Justin Scott, IDA Science and Technology Policy Institute, *Additive manufacturing: Status and opportunities*, March 2012.

Graphic: Deloitte University Press | DUPress.com

Fonte: Delloite University Press

1.7 Fundamentos da manufatura aditiva - Aplicações em potencial

INDUSTRIES	CURRENT APPLICATIONS	POTENTIAL FUTURE APPLICATIONS
COMMERCIAL AEROSPACE AND DEFENSE[17]	• Concept modeling and prototyping • Structural and non-structural production parts • Low-volume replacement parts	• Embedding additively manufactured electronics directly on parts • Complex engine parts • Aircraft wing components • Other structural aircraft components
SPACE	• Specialized parts for space exploration • Structures using light-weight, high-strength materials	• On-demand parts/spares in space • Large structures directly created in space, thus circumventing launch vehicle size limitations
AUTOMOTIVE[18]	• Rapid prototyping and manufacturing of end-use auto parts • Parts and assemblies for antique cars and racecars • Quick production of parts or entire	• Sophisticated auto components • Auto components designed through crowdsourcing
HEALTH CARE[19]	• Prostheses and implants • Medical instruments and models • Hearing aids and dental implants	• Developing organs for transplants • Large-scale pharmaceutical production • Developing human tissues for regenerative therapies
CONSUMER PRODUCTS/RETAIL	• Rapid prototyping • Creating and testing design iterations • Customized jewelry and watches • Limited product customization	• Co-designing and creating with customers • Customized living spaces • Growing mass customization of consumer products

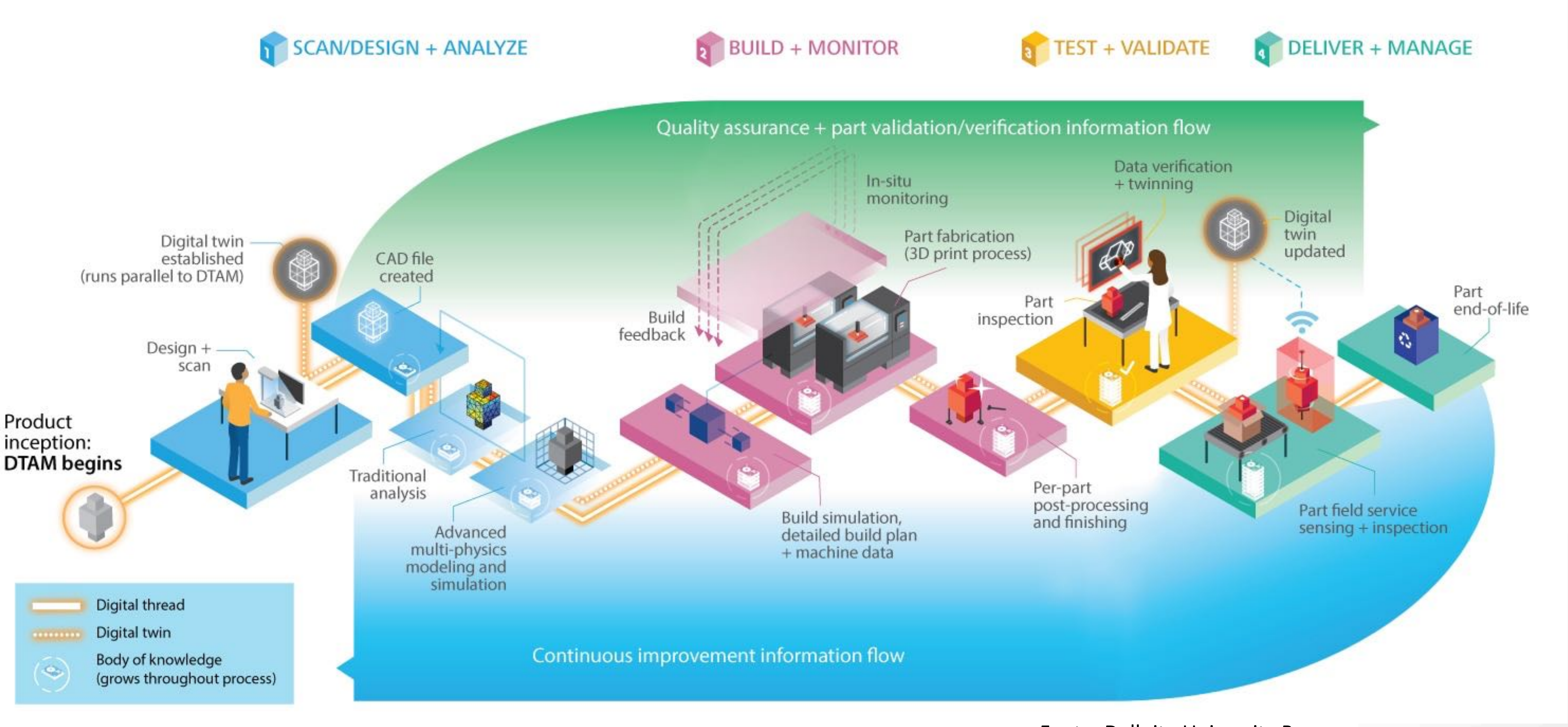
Sources: Deloitte analysis; CSC, *3D printing and the future of manufacturing*, 2012.

Graphic: Deloitte University Press | DUPress.com

Tema	Link
3D opportunities for product design	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-product-design-and-development.html
3D opportunities and the digital thread	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-digital-thread-in-manufacturing.html
3D opportunities for scan, design and analyze	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-digital-thread-in-manufacturing-scan-design-analyze.html
3D opportunity and cyber risk management	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-cyber-risk-management.html
3D opportunity for production	https://www2.deloitte.com/insights/us/en/deloitte-review/issue-15/additive-manufacturing-business-case.html
3D opportunity for tooling	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-opportunity-in-tooling.html
3D opportunities for quality assurance and parts qualification	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-quality-assurance-in-manufacturing.html
3D opportunity for the supply chain	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-printing-supply-chain-transformation.html
3D opportunities for end-user products	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-end-use-products.html
3D opportunities for life cycle assessments	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-in-lca-analysis.html
3D opportunity for business capabilities	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-business-capabilities.html
3D opportunity for electronics	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-printed-electronics.html
3D opportunities for aerospace and defense	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-opportunity-in-aerospace.html
3D opportunities for automotive industry	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-opportunity-in-automotive.html
3D opportunities for technology, media and telecommunications	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-in-technology-media-telecom-tmt-industry.html
3D opportunities for food	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-in-the-food-industry.html
3D opportunity for healthcare	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-fda-regulations-medical-devices.html
3D opportunities for medical technology	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-opportunity-in-medtech.html
3D opportunity for life	https://www2.deloitte.com/insights/us/en/deloitte-review/issue-19/3d-printing-for-humanitarian-action.html
3D opportunity for standards	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-standards-for-3d-printed-products.html
3D opportunity for engineers	https://www2.deloitte.com/insights/us/en/deloitte-review/issue-18/behavioral-research-for-3d-printing-adoption.html
3D opportunities for talent gap	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-talent-gap-workforce-development.html
3D opportunities for intellectual property and risks	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-intellectual-property-risks.html
3D opportunity for blockchain	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-blockchain-in-manufacturing.html
3D opportunity for adversaries	https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/national-security-implications-of-additive-manufacturing.html

2. Digital Thread para manufatura aditiva (DTMA)

Definição



Fonte: Delloite University Press

https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-digital-thread-in-manufacturing.html

2. Digital Thread para manufatura aditiva (DTMA)

Gestão do risco cibernético

Table 2. Examples of AM-specific cybersecurity concerns

AM-SPECIFIC CYBERSECURITY CONCERNS	POTENTIAL IMPACTS
Design files stolen	• Theft of IP or strategic plans • Reputation damage
Design files changed to build flaws in parts	• Destruction of critical infrastructure • Reputation damage • Threats to life/safety
Unauthorized objects printed	• Theft of IP or strategic plans (counterfeiting) • Reputation damage
Altering toolpath to deposit materials incorrectly	• Destruction of critical infrastructure • Reputation damage • Threats to life/safety
Printers taken offline	• Business disruption
IP-protected objects printed without payment or permission	• Theft of IP or strategic plans (counterfeiting) • Financial theft
Dangerous or illegal objects printed (e.g., weapons)	• Threats to life/safety
Digital twin hacked (e.g., to compromise maintenance)	• Destruction of critical infrastructure • Business disruption • Threats to life/safety
Digital thread hacked (e.g., to affect quality control)	• Reputation damage • Threats to life/safety

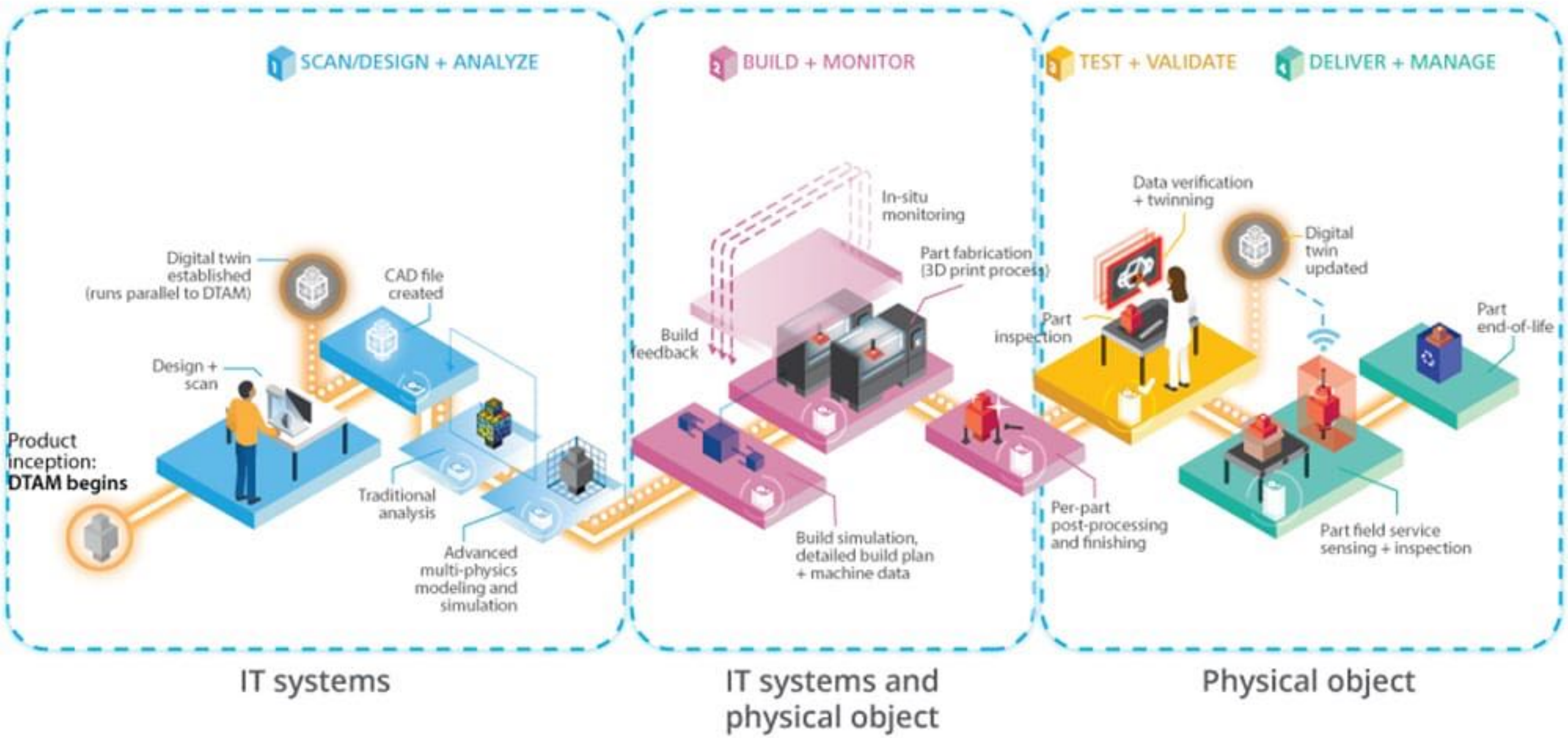
Fonte: Delloite University Press

https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-digital-thread-in-manufacturing.html

2. Digital Thread para manufatura aditiva (DTMA)

Gestão do risco cibernético

Figure 3. Cyber risks along the digital thread



Source: Mark J. Cotteleer, Stuart Trouton, and Ed Dobner, *3D opportunity and the digital thread*, Deloitte University Press, March 3, 2016, http://dupress.com/articles/3d-printing-digital-thread-in-manufacturing/.

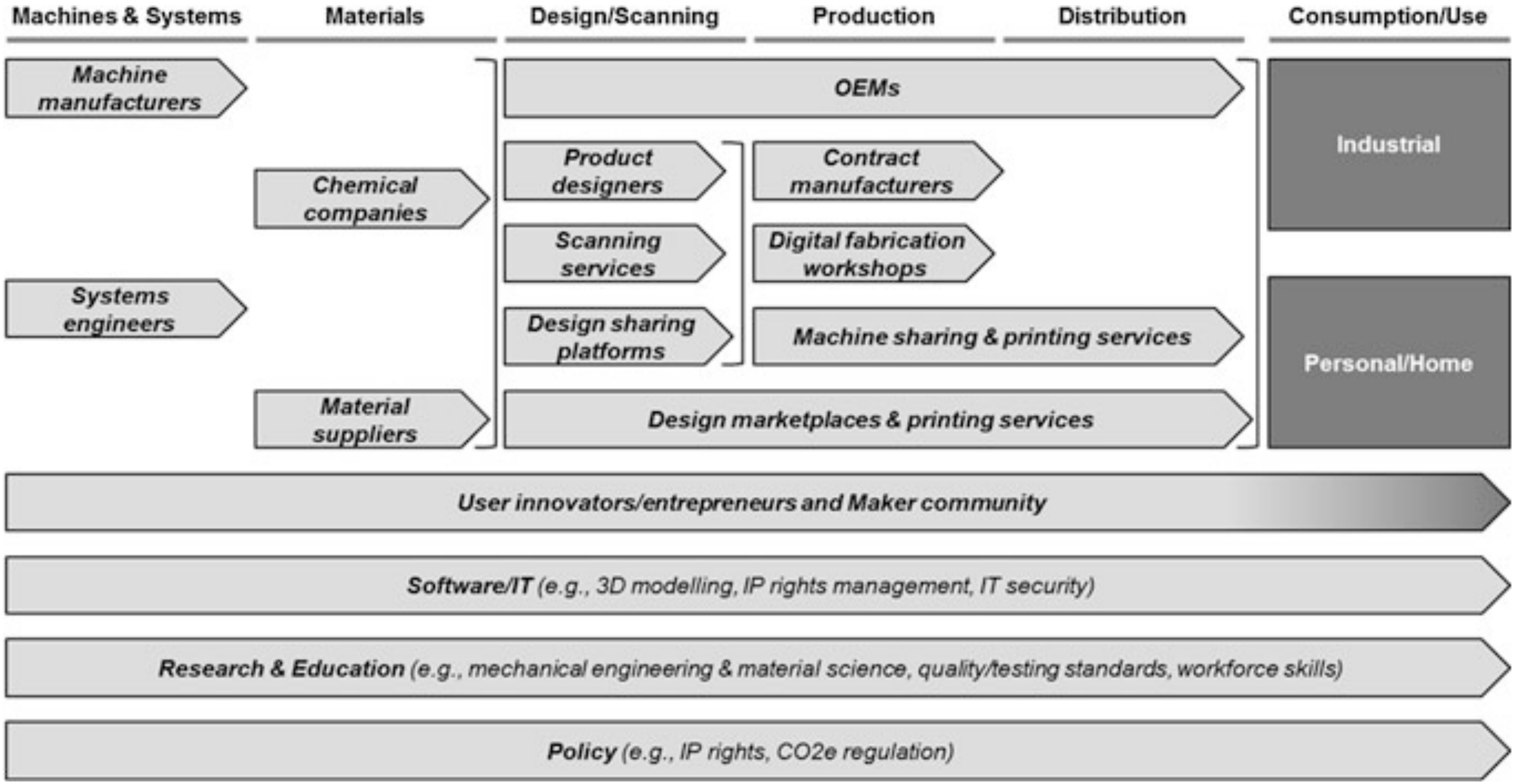
Graphic: Deloitte University Press | DUPress.com

Fonte: Delloite University Press

https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/3d-printing-digital-thread-in-manufacturing.html

3. Novos modelos de negócios

Modelos de negócio com manufatura aditiva



Fonte, Piller et al., 2015 DOI 10.1007/978-3-319-12304-2_4

Fig. 4.1 AM ecosystem

J. Savolainen and M. Collan, How Additive Manufacturing Technology Changes Business Models? – Review of Literature , Additive Manufacturing 32 (2020) 101070 , https://doi.org/10.1016/j.addma.2020.101070

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