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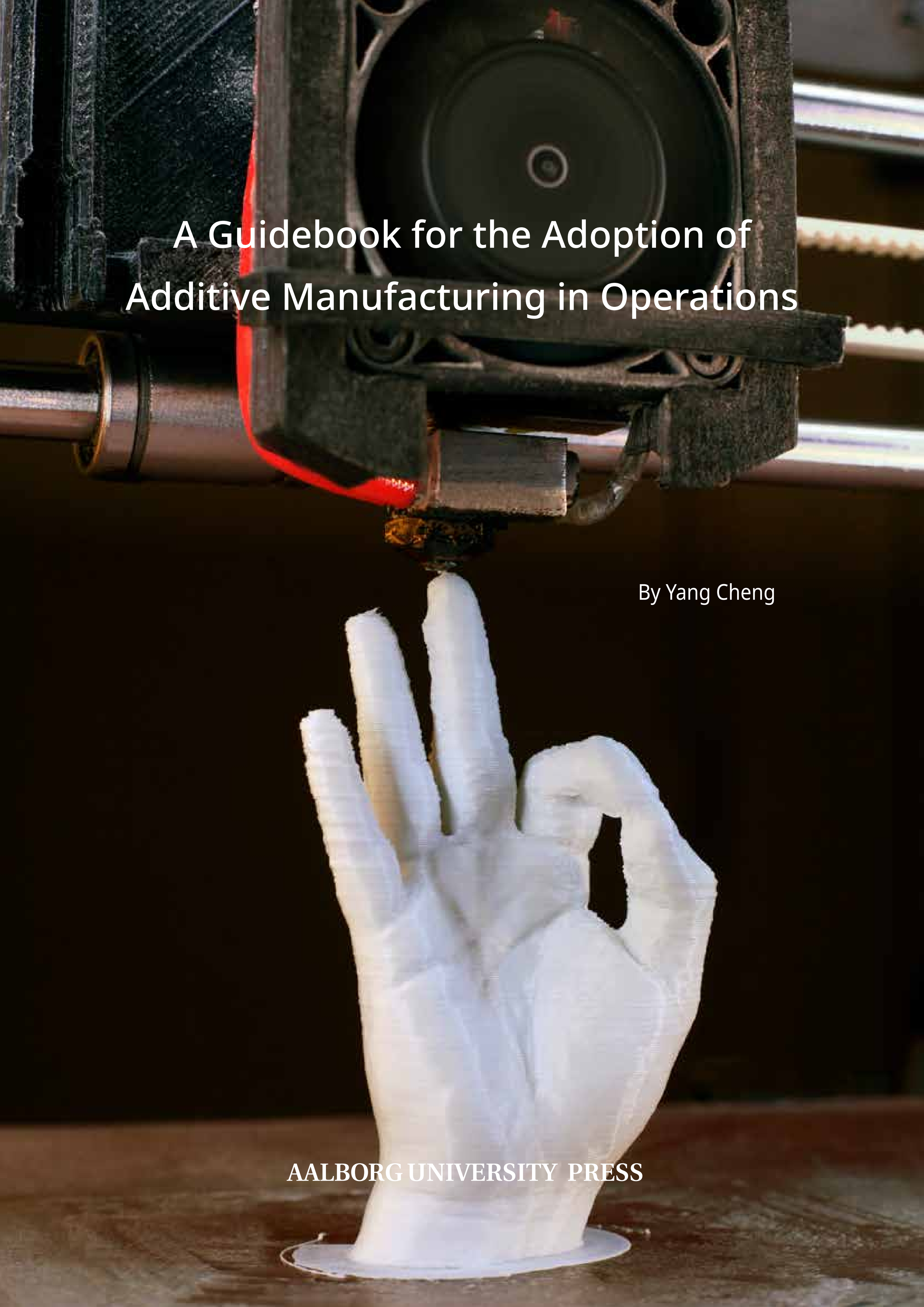

A Guidebook for the Adoption of Additive Manufacturing in Operations

By Yang Cheng

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A Guidebook for the Adoption of Additive Manufacturing in Operations

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Index

Figures

1. Introduction to Additive Manufacturing

Additive Manufacturing (AM) is a technology used to create objects or components by adding layer upon layer in precise geometric shapes. The name of the technology actually demonstrates this layer upon layer procedure, through the term 'additive', and shows the difference between AM and traditional subtractive manufacturing, where layers of materials are removed and not added. Through AM, one can print in a variety of materials such as metal, plastic, and even advancing into living biological tissue. AM is often referred to as 3D printing because of the ability to print objects in three dimensions. The technology uses Computer-Aided Design (CAD) software to design the objects so that the AM tool can read (in) the data from the CAD file and print the requested object (Li et al., 2017).

1.1 The History of AM

AM is not as new as some might think because the first 3D printers were developed back in the 1980s by Dr. Hideo Kodama from Nagoya Municipal Industrial Research Institute. He created a photopolymer rapid prototyping system, which used vat photopolymer as material and exposed it to UV lighting in order to harden the material. Since then, various AM technologies have been developed. An overview of the historical events within AM can be seen in Figure 1 (Wohlers & Gornet, 2016).

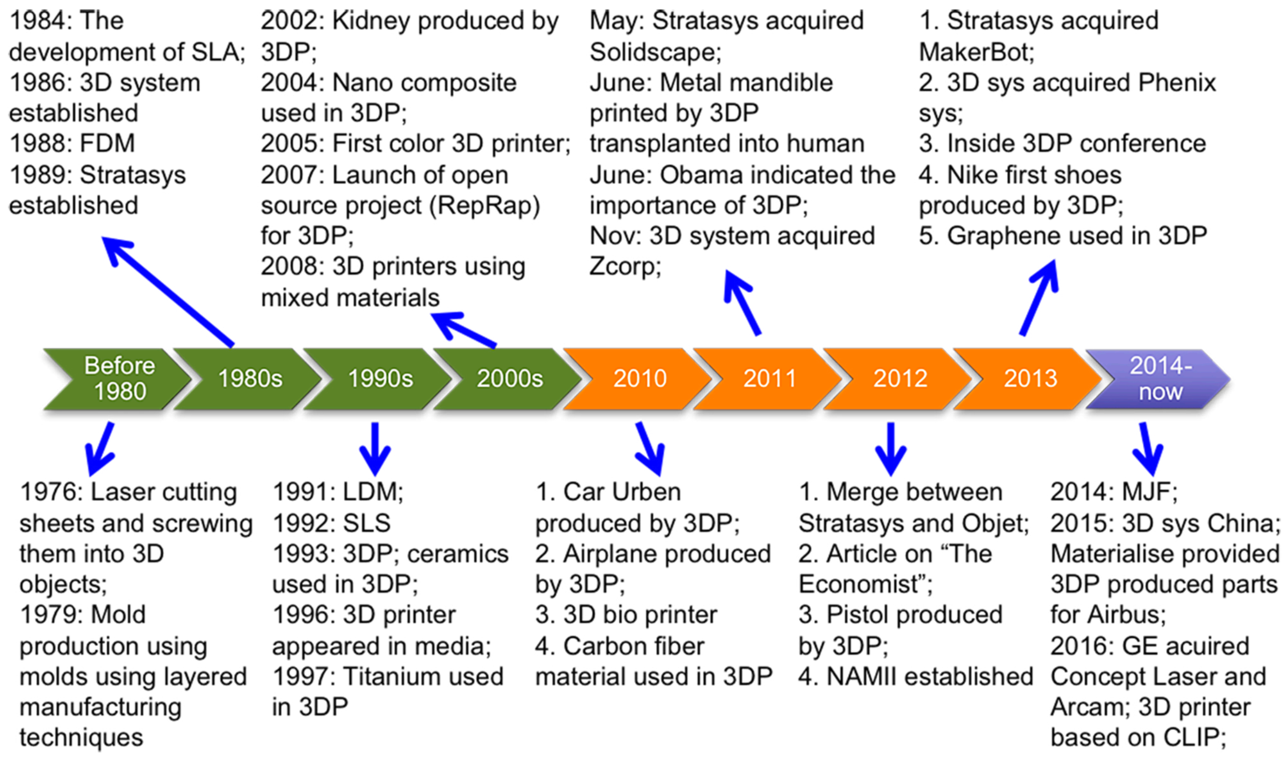


Figure 1: *The history of AM from 1980 to the present.*

1.2 AM Technologies

Since the 1980s, at least seven categories of AM technologies have been developed, which are shown in Figure 2 together with their characteristics (3D Hubs, 2021a).

7 Families of Additive Manufacturing (according to ISO/ASTM52900-15)			
Vat Polymerization (VAT)	Powder Bed Fusion (PBF)	Binder Jetting (BJ)	Material Jetting (MJ)
Alternative Names: SLA – Stereolithography Apparatus DLP – Digital Light Processing 3SP – Scan, Spin, and Selectively Photocure CLIP – Continuous Liquid Interface Production	**Alternative Names:** SLS – Selective Laser Sintering; DMLS – Direct Metal Laser Sintering; SLM – Selective Laser Melting; EBM – Electron Beam Melting; SHS – Selective Heat Sintering; MJF – Multi-Jet Fusion	**Alternative Names:** 3DP – 3D Printing ExOne Voxeljet	**Alternative Names:** Polyjet SCP – Smooth Curvatures Printing MJM – Multi-Jet Modelling Project
Description: A vat of liquid photopolymer resin is cured through selective exposure to light (via a laser or projector), which initiates polymerisation and converts the exposed areas to a solid part.	**Description:** Powdered material is selectively consolidated by melting it together using a heat source such as a laser or an electron beam. The powder surrounding the consolidated part acts as a support material for overhanging features.	**Description:** Liquid bonding agents are selectively applied onto thin layers of powdered material to build up parts layer by layer. The binders include organic and inorganic materials. Metal or ceramic powdered parts are typically fired in a furnace after they are printed.	**Description:** Droplets of material are deposited or cured layer by layer to make parts. Common varieties include jetting a photocurable resin and curing it with UV light, as well as jetting thermally molten materials, which solidify in ambient temperatures.
Strengths: High level of accuracy and complexity Smooth surface finish Accommodates large build areas Weaknesses: Produces relatively brittle parts, not suitable for functional usage Degrades with exposure to sunlight Removal of support marks required	Strengths: High level of complexity Powder acts as a support material Wide range of materials Ideal for functional prototypes/ high-end engineering applications Small batch production capabilities Weaknesses: Higher cost than FDM or SLA Specialised CAD software Slower turnaround due to batch production/limited build volume Grainy surface & internal porosity A risk of dimensional shrinkage by up to 3-3.5%	Strengths: Low cost batch production of metal parts No need for support structure Allows for full colour printing High productivity Uses a wide range of materials Weaknesses: Inferior material properties compared to DMSL/SLM Design restriction due to post-processing Fine details may not be printable	Strengths: High level of accuracy & very fine details Injection moulding-like finish Allows for full colour parts Enables multiple materials in a single part Weaknesses: The most expensive plastic 3D printing process Mechanical properties degrade over time Produces relatively brittle parts
Typical Materials: UV-curable photopolymer resins	**Typical Materials:** Plastics, metal and ceramic powders, and sand	**Typical Materials:** Powdered Plastic, Metal, Ceramics, Glass, and Sand	**Typical Materials:** Photopolymers, polymers, waxes
Sheet Lamination (SL)	Material Extrusion (ME)	Direct Energy Deposition (DED)	Hybrid
Alternative Names: LOM – Laminated Object Manufacture SDL – Selective Deposition Lamination UAM – Ultrasonic Additive Manufacturing	**Alternative Names:** FFF – Fused Filament Fabrication FDM – Fused Deposition Modelling	**Alternative Names:** LMD – Laser Metal Deposition LENS – Laser Engineered Net Shaping	**Alternative Names:** AMBIT – Created by Hybrid Manufacturing Technologies
Description: Sheets of material are bonded, stacked, and laminated together to form an object. The lamination method can be adhesive or chemical (paper/plastics), ultrasonic welding or brazing (metals). Unneeded regions are cut out layer by layer and removed after the object is built.	**Description:** Material is extruded through a nozzle or orifice in tracks or beads, which are further combined into multilayer models. Common varieties include heated thermoplastic extrusion (similar to a hot glue gun) and syringe dispensing.	**Description:** Powder or wire is fed into a melt pool, which has been generated on the surface of the part, where it adheres to the underlying parts, or layers, by using an energy source such as a laser or an electron beam. This is essentially a form of automated build-up welding.	**Description:** Laser metal deposition (a form of DED) is combined with CNC machining, which allows additive manufacturing and subtractive manufacturing to be performed in a single machine so that parts can utilise the strengths of both processes.

Strengths: High volumetric build rates Relatively low cost (non-metals) Ease of material handling Allows for combinations of metal foils, including embedding components Weaknesses: Limited material use The need for post-processing due to varying finishes	Strengths: Inexpensive and economical Fast turnaround Allows for multiple colours Can be used in an office environment Parts have good structural properties Weaknesses: Limited dimensional accuracy Visible layer lines (can be post-processed) Anisotropic mechanical properties	Strengths: Not limited by direction or axis Effective for repairs and adding features Multiple materials in a single part Highest single-point deposition rates Weaknesses: Not ideally suited for the production of parts from scratch Trade-off between speed and accuracy	Strengths: Smooth surface finish and high productivity Geometrical and material freedoms of DED Automated in-process support for removal, finishing, and inspection
Typical Materials: Paper, plastic sheets, and metal foils/tapes	**Typical Materials:** Thermoplastic filaments and pellets, liquids, and slurries (syringe types)	**Typical Materials:** Metal wire and powder, with ceramics	**Typical Materials:** Metal powder and wire, with ceramics

Figure 2: 7 families of additive manufacturing

In short, and as illustrated in Figure 3, VAT and SL are more suitable for making objects that need to have complex geometries and smooth surface finishes, but not suitable for making functional objects that have to be durable under different conditions, such as constant pressure, UV light, temperature resistance, water resistance, tensile strength, etc. In contrast, ME and DED are more suitable for making functional objects that have to be durable under different conditions, but not suitable for making objects that need to have complex geometries and smooth surface finishes. In terms of detail/surface finish and application/durability, MJ seems to be more suitable, but is generally more expensive.

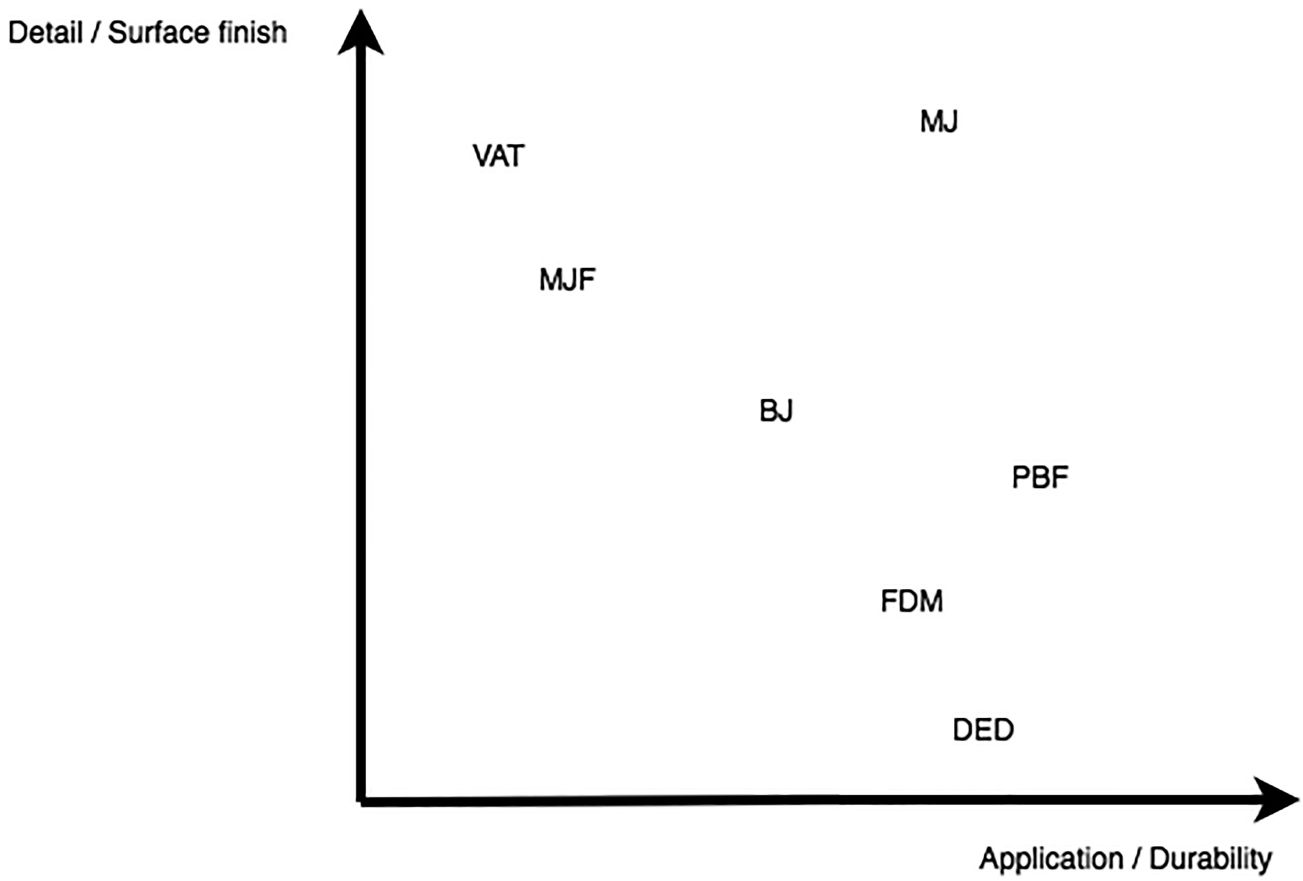


Figure 3: The positions of the 7 families of AM technologies.

1.3 AM Processes

Nevertheless, the seven families of AM technologies generally follow the same manufacturing processes, which include eight steps as illustrated in Figure 4.

***Figure 4:** 8-step manufacturing processes of AM.*

1. The first step is concerned with modelling the objects/components that need to be 3D printed. This can be done by using any kind of CAD modelling software.

2. The second step in this process is the conversion of the CAD files to a STL file format. STL files are supported by almost every industrial 3D printer.

3. The third step revolves around transferring the STL file to the 3D printer. It is in this specific step that the correct size and position of the object/component is chosen.

4. The fourth step concerns the setup of the 3D printer. It is very important that the printer is set up properly for the specific build process. Settings such as material constraints, energy source, layer thickness, timings, temperature and cooling have to be accurate.

5. The fifth step is where the 3D printer starts to print.

6. The sixth step is where the parts are removed manually by people. Therefore, it is important that the 3D printer is safe to interact with, meaning that it must be fully stopped and have a low enough temperature for humans to interact with it.

7. The seventh step is concerned with post-processing. This is where skilled people clean the parts and separate them from their supportive structures.

8. The last step in the AM process revolves around the application. The different parts might require treatment, such as painting, before they can be used. Another requirement might be assembly since some 3D printed components are parts of a bigger object.

1.4 Advantages and Disadvantages of AM

AM has many advantages compared to traditional manufacturing technologies. However, it does have disadvantages as well. The following section aims at giving a better overview of the advantages and disadvantages of AM in general (Berman, 2012).

The advantages of AM:	The disadvantages of AM:
• Being capable of building complex geometries in a single process that cannot be fabricated by any other means; offering the utmost geometrical freedom in engineering design and thus customised products. • Ability to speed up product design and easily share and modify designs. • Eliminating the expensive tooling required by forming processes like moulding, forging, or stamping. • Creating functional components without the need for assembly, saving both production time and cost and reducing complexity in business. • Minimal inventory risk as there is no unsold finished goods inventory. • Offering reduced waste, a minimal use of harmful chemicals, the possibility to limit energy used, the use of recycled materials, and a reduced carbon footprint. • Decentralising the production. The print can be produced all over the world, where the design can be sent and then printed. • It is possible to customise every single product to customer needs.	• Higher costs than traditional manufacturing in regard to both the machinery and the material costs. • Only limited materials, colours, and surface finishes are available for AM, meaning that it cannot compete with traditional manufacturing in regard to these choices. • Low precision compared to traditional manufacturing technologies. • High calibration effort. • The quality of different components needs improvement; therefore, it is often necessary to rework these components with the help of support structures. • Limited strength, resistance to heat and moisture, and colour stability. This depends on what materials are used for AM.

Figure 5: *The advantages and disadvantages of AM.*

In short, and as illustrated in Figure 6, AM is more suitable for producing products with low production volumes, small part sizes, and complex designs.

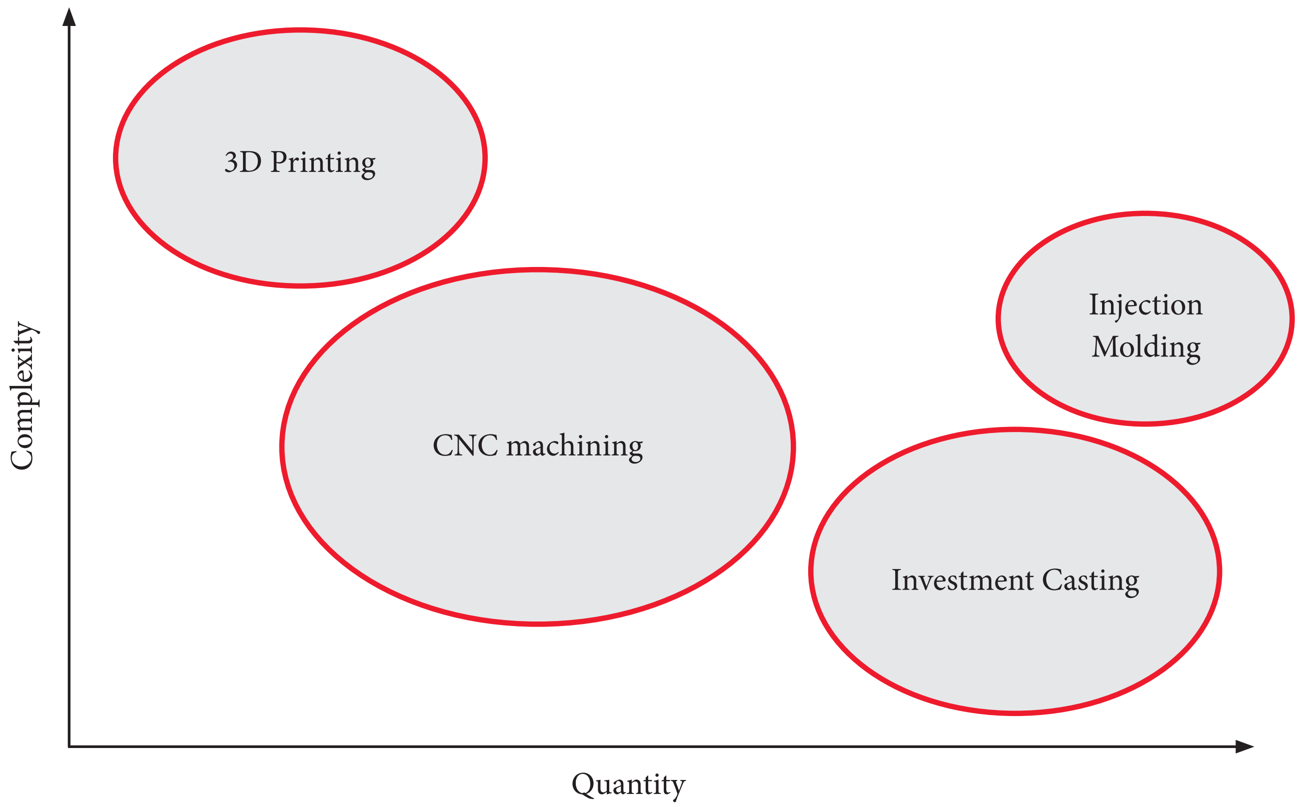


Figure 6: *Suitability of AM technologies.*

1.5 Three Applications of AM in the Industrial Setting

In general, AM can be used for *rapid prototyping, rapid tooling, and rapid manufacturing* (Attaran, 2017). Below, each application will be elaborated further and together with its associated benefits (and more benefits will be elaborated in section 2.1).

- *Rapid Prototyping.* This approach is concerned with the use of AM to accelerate the prototyping process. The technique provides the companies with the opportunity to quickly design and produce a prototype of a product, part, or component. The main advantages of rapid prototyping are faster prototyping, potential cost benefits, and enhanced visualisation by, rapidly, having a tangible output to display for potential customers. Faster prototyping means that issues are detected earlier which in return can save money, so the benefits influence each other. Because of the faster and cheaper prototyping, it is possible to create many relatively cheap design changes throughout the development of the product.

- *Rapid tooling.* This approach is concerned with using AM to produce tools or moulds for traditional manufacturing directly or indirectly. The direct tooling consists of having moulds printed and making them ready for use in traditional manufacturing, while the indirect tooling consists of creating moulds, which are used to create the final moulds. The advantages of rapid tooling lie within the speed and cost of production. Other benefits include the production time for a tool being short and the product potentially being constructed in a vast array of materials. Furthermore, the discovery and troubleshooting of issues in the production might be caught at a much earlier stage. However, if the volume of production is high, the production of expensive tooling can be considered viable since rapid tooling is not cost efficient in a mass production of tools. Besides, the product life cycle of the AMed tool is generally shorter than the product life cycles of conventional tools.

- *Rapid manufacturing.* This approach is concerned with using AM to produce final or functional products. Rapid manufacturing is especially convenient in the process of reducing the overall lead time and introducing a certain level of not only machine flexibility, but also operation, process, and product flexibility. This can even lead to significant restructuring of the supply chain, especially related to spare parts. Nevertheless, AM is not feasible, when large quantities of products must be produced. Besides, it is especially important to be aware of factors such as material properties, due to the nature of end products.

2. The Adoption of AM in Operations

As a new industrial revolution, AM implies a completely new system transforming the very notion of manufacturing in a 'hugely creative and disruptive' way. Further, its adoption can lead to profound changes in the ways many products are designed, developed, produced, delivered, and supported. Nevertheless, its adoption is not a simple task. It contains three steps that companies have to follow. These three steps are corresponding to three questions that companies need to ask themselves in the process of adopting AM (see Figure 7):

- What the company wants to achieve by adopting AM?
- Whether it is possible to use AM in operations?
- Whether it is economically better to use AM in operations?

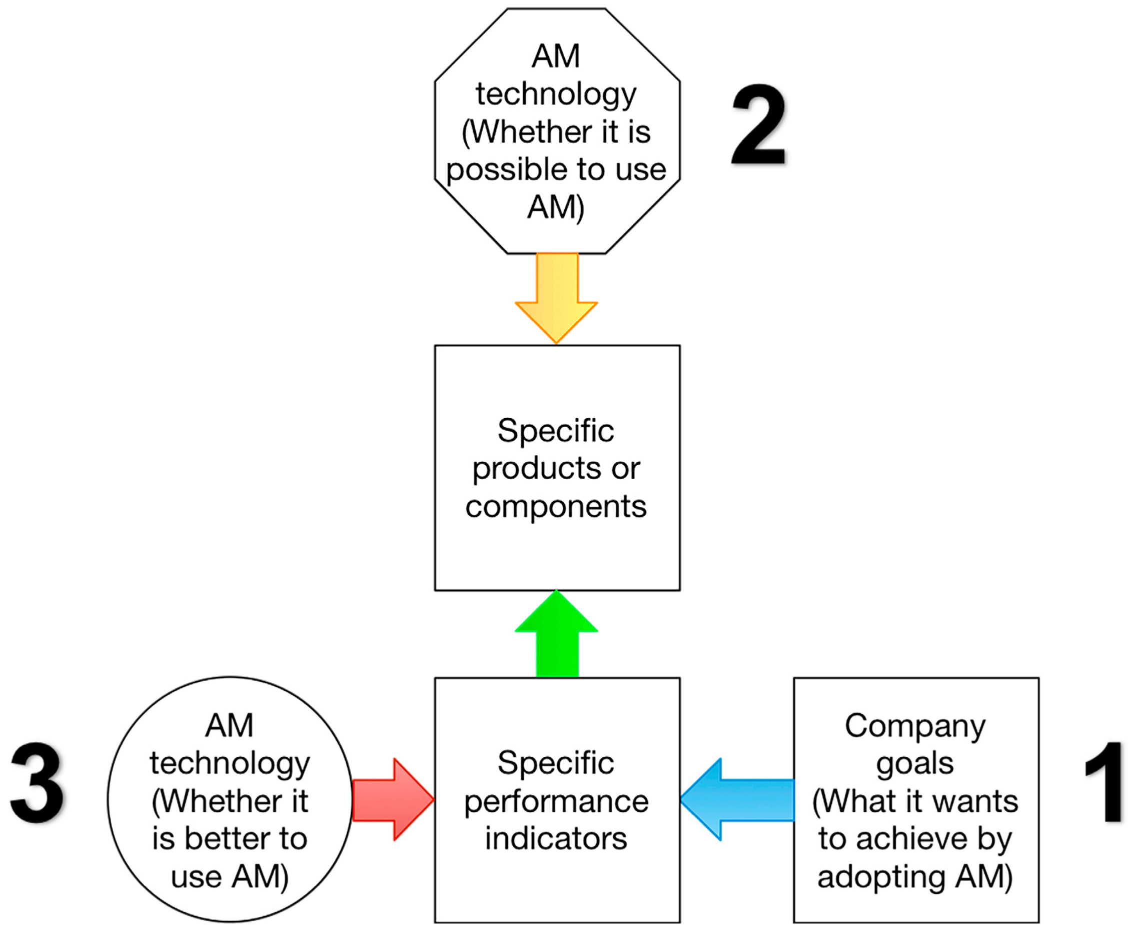


Figure 7: The three questions regarding AM adoption

2.1 Question 1: What the Company Wants to Achieve by Adopting AM?

As described in section 1.5, AM can be used for three types of application in the industrial setting. As illustrated in Figure 8, each type of application can bring different operational benefits to companies.

For prototype:	**For tooling (especially with traditional manufacturing):**	**For Manufacturing:**
• Geometric freedom • Functional integration • Prototype development time reduction • Reduce overall development time • Reduce prototyping costs • Flexibility to make prototypes anytime • Improve the overall design of the product • Reduce product development risks • Improve customer involvement • Improve communication between R&D and production through visualisation	• Geometric freedom • Functional integration • Few number of tools • Fulfil short warning changes from customers • Tooling cost reduction • Reduce process steps in tooling production • Tool development lead time reduction • Improve flexibility in tool making • Digital storage of tools • Reduce coolant usage in the tool • Reduce tool changeover time	• Machine cost reduction • Inventory/delivery cost reduction with digital inventory • Lead (delivery) time reduction • Supply risk reduction • Downtime (cost) reduction • Reduce carbon footprint and material waste across life cycle • Reduce potential loss of business • Shorter and more transparent supply chain • Improved service level and Increased availability of suitable materials (reduction of stock-out cost) • Offer more customised products • Flexible production line for small-batch

Figure 8: *Benefits brought by the three types of application of AM in the industrial setting.*

As the first step of AM adoption, companies have to be clear about what operational targets they would like to achieve by adopting AM, and for which they need to understand their businesses better, e.g., by mapping their businessestargets in a value stream map. More focus needs to be put on customers, and the characteristics of AM need to be taken into account, in order to identify potential business opportunities in terms of what companies can offer to customers based on the adoption of AM. These business opportunities should be further translated into operational targets, which could be among the operational benefits listed in Figure 8. Afterwards, companies can reversely determine which applications they have to prioritise. Certainly, it is also possible and even suggested to simultaneously focus on several applications if the resources allow it.

Besides, companies also have to think about whether they would like to use ***AM for developing and/or producing a new product or an existing product***. If it is an existing product to be produced, companies can move directly to addressing the next two questions illustrated in Figure 7, in order to evaluate whether it is possible and profitable to use AM for the company's tooling or manufacturing processes. Once approved, the product might need to be redesigned according to AM characteristics. In contrast, if it is a new product to be developed and produced, companies have to assess whether they want to use AM only in their product development or even for end product production, which correlates to four scenarios (see Figure 9), namely:

- Using AM in product development, but not in manufacturing. This adds the potential applications of AM using rapid tooling in combination with rapid prototyping, or simply only using rapid prototyping.

- Using AM in product development as well as in manufacturing. This creates the potential of using AM for rapid manufacturing of end products as well as for rapid prototyping.

- Not using AM for neither product development nor manufacturing. This creates no potential for AM and thus only refers to traditional manufacturing.

- Using AM for manufacturing, but not product development. This is not justified because if it were to be manufactured using AM, it would not be justified to design the product in the traditional way.

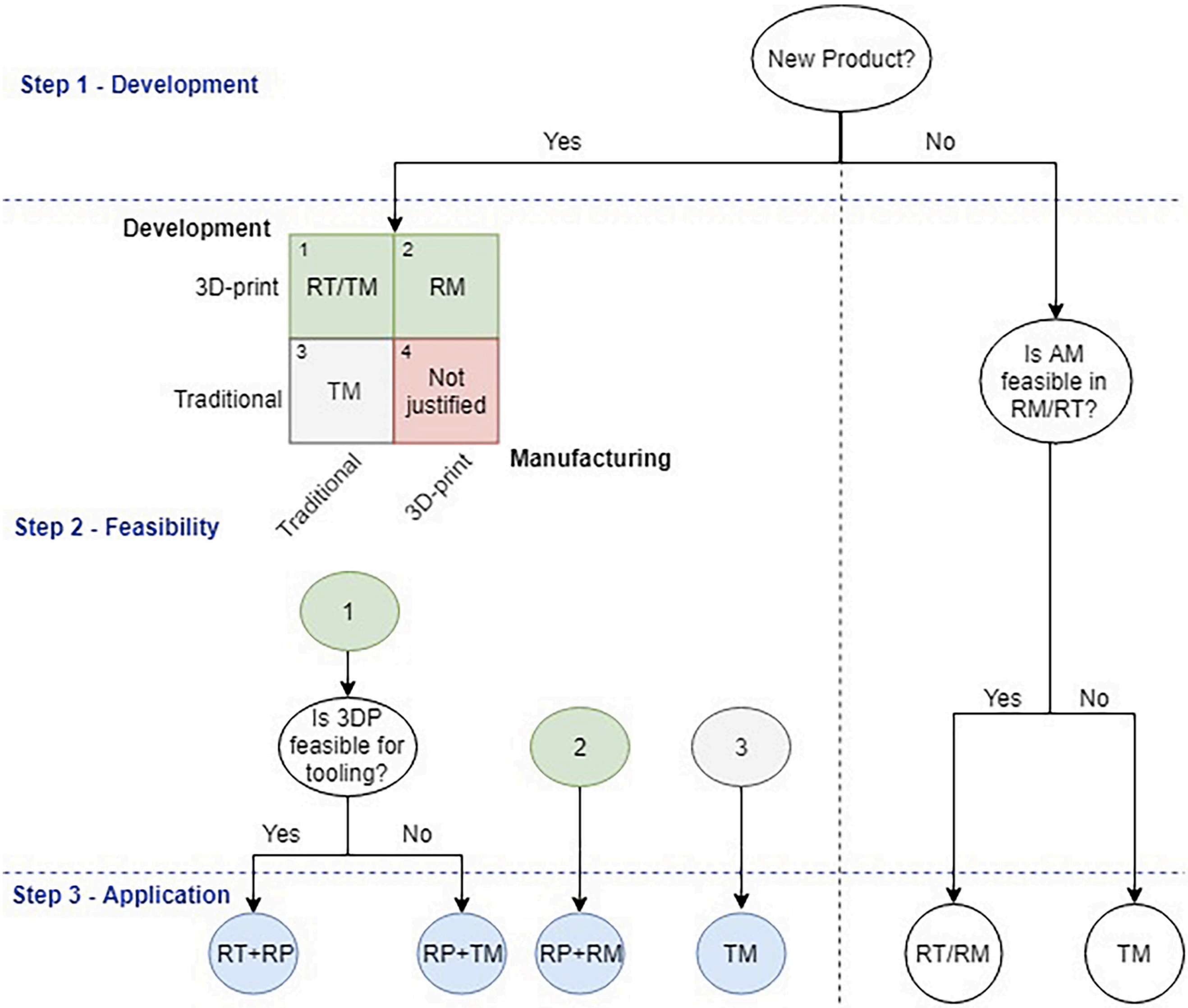


Figure 9: *Scenarios to be considered when determining the applications of AM (RP: Rapid Prototyping; RT: Rapid Tooling; RM: Rapid Manufacturing).*

The reason to distinguish between these scenarios is that despite the great design freedom offered by AM, some restrictions do apply: "Anything can be 'drawn' in 3D on a digital canvas, but not everything can be 3D printed; and even the prototype can be 3D printed, but it might not be suitable to be produced by traditional manufacturing approach" (3D Hub, 2021b). Thus, companies have to fully understand that AM indeed challenges some of the more traditional thinking of product design. On the one hand, it offers many advantages related to prototype/product development, including:

- Availability of complex geometries to achieve design goals, where the trade-off of cost or time is eliminated.

- Possibility of consolidating different parts and integrating features into more complex parts while also avoiding assembly issues.

- Enabling designers to make products/parts with multifunctional designs.

- Diminishing some constraints put upon the designers, when utilising AM, compared to traditional manufacturing.

On the other hand, it also calls for the attention to some key design considerations, as suggested by 3D Hub (2021b), including:

- **Overhangs** are areas of a model that are either partially supported by the layer below or not supported at all. There is a limit on the angle every printer can produce without the need of support material, while layers printed over support usually have a rougher surface finish.

- **Wall thickness** always adds thickness to your models. Walls with thickness greater than 0.8 mm can be printed successfully with all processes.

- **Warping:** The heating and cooling of material can cause the parts to warp while printing. To avoid warping, a good practice is to avoid large flat surfaces and add rounded corners to your 3D models.

- **Level of detail:** The minimum level of detail is connected to the capabilities and mechanics of each 3D printing process and to the selected layer height; thus, make the right choice.

Other more specific design guidelines for each AM process are summarised in a poster developed by 3D Hub (2021b), and see Figure 10.

DESIGN RULES FOR 3D PRINTING

3D HUBS

	Supported Walls	Unsupported Walls	Support & Overhangs	Embossed & Engraved Details	Horizontal Bridges	Holes	Connecting /Moving Parts	Escape Holes	Minimum Features	Pin Diameter	Tolerance
	Walls that are connected to the rest of the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.	Features on the model that are raised or recessed below the model surface.	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.	The recommended clearance between two moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
Fused Deposition Modeling	0.8 mm	0.8 mm	45°	0.6 mm wide & 2 mm high	10 mm	Ø2 mm	0.5 mm		2 mm	3 mm	±0.5% (lower limit ±0.5 mm)
Stereo-lithography	0.5 mm	1 mm	support always required	0.4 mm wide & high		Ø0.5 mm	0.5 mm	4 mm	0.2 mm	0.5 mm	±0.5% (lower limit ±0.15 mm)
Selective Laser Sintering	0.7 mm			1 mm wide & high		Ø1.5 mm	0.3 mm for moving parts & 0.1 mm for connections	5 mm	0.8 mm	0.8 mm	±0.3% (lower limit ±0.3 mm)
Material Jetting	1 mm	1 mm	support always required	0.5 mm wide & high		Ø0.5 mm	0.2 mm		0.5 mm	0.5 mm	±0.1 mm
Binder Jetting	2 mm	3 mm		0.5 mm wide & high		Ø1.5 mm		5 mm	2 mm	2 mm	±0.2 mm for metal & ±0.3 mm for sand
Direct Metal Laser Sintering	0.4 mm	0.5 mm	support always required	0.1 mm wide & high	2 mm	Ø1.5 mm		5 mm	0.6 mm	1 mm	±0.1 mm

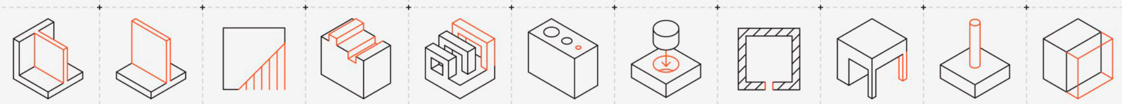


Figure 10: *A summary of the most important design guidelines for each AM process. 3D Hub (2021b)*

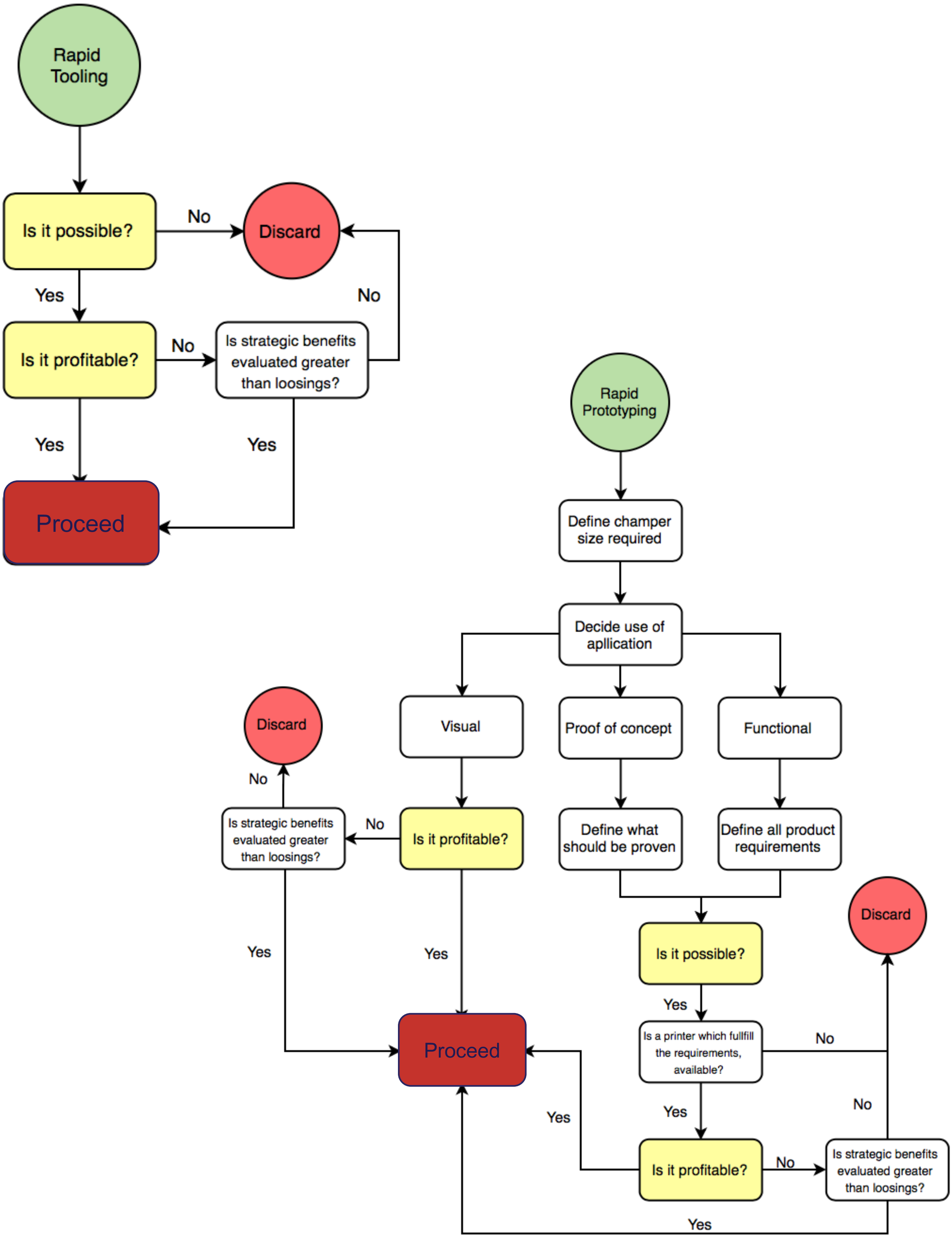
Once companies decide which types of applications of AM (which can be one, two, or three types of applications at the same time) to focus on, they can follow the approaches illustrated in Figure 11 to move forward in terms of their adoption of AM. Specifically, if companies choose to focus on rapid tooling and manufacturing, the approach will be quite straightforward: thus, moving directly to answer two questions (i.e. whether it is possible and profitable to use AM in operations) in sequence. In contrast, if companies focus on rapid prototyping, the approach is more complicated as companies have to further determine what kinds of usage categories they would like to pursuit:

- **Visual:** As its name suggests, only for visual purposes. This means that it cannot function as an actual part, but only for visualising parts. This could be used for customer purposes as well as internal evaluation purposes.

- **Proof of concept:** A middle course, whereas the idea is to prove if the concept works. This means that the printer only needs to meet some of the requirements. An example of this could be a pump wheel where the printer can print the tensile requirements of and for the pump wheel to function, but the pump wheel does not meet the humidity requirements.

- **Functional:** A very complex matter, due to the fact that the parts produced need to meet all the requirements of the product.

If companies choose to use AM for visual prototyping, they move directly to address the question related to profitability since they will not be constrained by the limitations of materials and printers. Instead, they can choose the simplest and cheapest AM technologies, as long as these technologies can produce models for visualisation. If companies choose to use AM for proof of concept and functional prototyping, they have to go through possibility and profitability analyses in sequence like those focusing on rapid tooling and manufacturing.



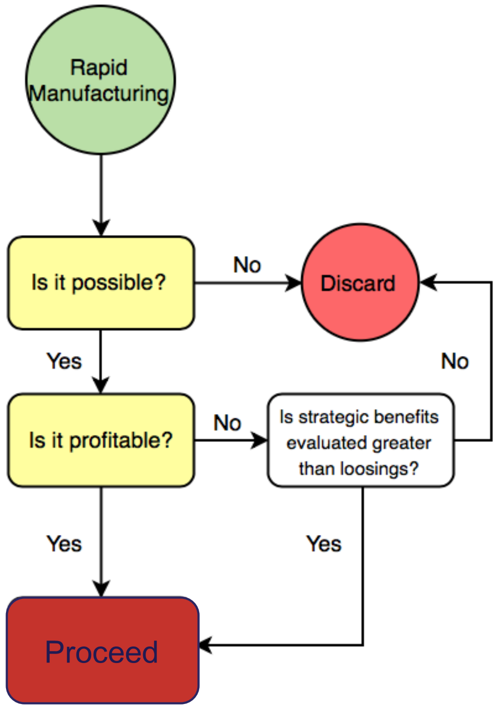


Figure 11: *The three approaches of AM adoption after choosing among RP, RT, and RM.*

2.2 Criteria and Methods for Addressing Questions 2 and 3

Nevertheless, no matter which approach companies follow, they have to find answers to whether it is possible and profitable to use AM in operations. In order to answer those two questions, companies essentially need to evaluate relevant criteria (e.g., Knofius et al., 2016), including:

- **Material availability (MA):** When companies adopt AM (except for visual prototypes), they must assure that the finished prototypes, tools, and/or products can live up to a given set of specifications, which, accordingly, have direct technical requirements for materials used in AM, in terms of e.g. tensile strength, resistance of humidity, resistance of temperature, conductivity, chemical resistance against polar and non-polar chemicals, UV resistance, surface smoothness, and flexural strength.

- **Printer availability (PA):** Once the materials used in AM are determined, the range of printers that can be used is determined as well. Nevertheless, companies still have to investigate other characteristics of printers, such as infill, speed, manufacturing cost, and the size of the parts that can be printed, in order to ensure appropriate printers are chosen.

- **Volume (V):** Production volume can be stated to be essential when calculating whether AM is a viable option or not, but it should also be noticed that it is not the single defining factor but only part of the equation. For example, although being said that AM is most appropriate for low volume production, this will not be the case if the unit price is low and/or the lead time is not critical.

- **Demand (volume) variation (DV):** Demand variation is, obviously, closely linked to demand volume itself and affects whether the demand is predictable or not, and how much it can vary. It can be argued whether the demand variation is a function of the volume itself or merely a stand-alone parameter. However, it is important for companies to understand their demand variation since AM might not be suitable if the demand is predictable due to considerations of cost and lead time.

- **Total cost (TC):** When dealing with any type of technology investment, cost is a relevant factor. However, total cost is different from case to case. It is defined based on the individual cost structure, and it is dependent on which costs are considered as internal and external, respectively. Here, the internal costs are connected to the production and the technical costs, whereas the external costs are the costs tied to the supply chain.

- **Criticality (lead time) (C):** This criterion is considered within the importance of lead time, regardless whether it is development time or delivery time. The lead time gains the majority of its magnitude due to its link to cost as a function of time. An example hereof could be the lost profit from e.g., a wind turbine standing still whilst, or due to, waiting for a crucial component.

- **Supply risk (SR)** is a major risk in all sorts of businesses because not getting supplied can lead to non-functional operations and profit loss. If the supply risk is fairly high, AM can have a positive effect by helping to balance this risk.

- **Geometric complexity (GC):** The complexity is 'free', when working with AM, and due to this, components with higher complexity stand to gain more from being AM'ed in terms of an overall reduction in production costs. However, geometric complexity cannot stand alone, when deciding whether or not the object should be produced through AM, but should be used in conjunction, or collaboration, with other criteria.

Among these criteria, MA and PA have a much higher decision power and are able to eliminate the possibility of adopting AM, while other criteria are equally important and there exists a trade-off among them. Besides, GC, SR, and MA are not quantitatively measurable, while other criteria are. These characteristics lead to the fact that different criteria need to be evaluated according to different methods; see Figure 12. Based on these criteria and methods, two questions regarding possibility and profitability analyses can be answered appropriately, which will be elaborated below.

Criteria	Method				
	Operational				Strategic
	Screening	Flowchart	MCDM	Business Case	Matrix
Demand Variation			X		
Volume			X	X	
Criticality			X	X	
Total Cost			X	X	
Geometric Complexity					X
Supply Risk					X
Printer Availability	X	X			
Material Availability	X	X			

Figure 12: *Different methods for criteria evaluation.*

2.3 Question 2 (Possibility Analysis): Whether it is Possible to Use AM in Operations?

The second question of AM adoption is concerned with whether it is possible for companies to use AM for producing specific prototypes, tools, and/or products which can be addressed by two different approaches:

- **Top-down** can be initiated with a large part population. It is suitable for companies that have already established large product portfolios with numerous components/products and want to examine which of them are best suited for AM.

- **Bottom-up** replies on the expertise of practitioners in order to realise AM might improve the characteristics of a specific item and hereafter assess the possibility. It is suitable for companies with no or a limited current product portfolio and/or a make-to-order strategy. Companies focusing on rapid prototyping have to follow this approach (Knofius et al., 2016).

No matter which approach companies follow, they have to consider two criteria, i.e., material availability and printer availability, which can be evaluated by using the methods *Screening* and *Flowchart*, as shown in Figure 12. Based on these criteria and methods, a general process model with three steps is proposed to guide the possibility analysis (see Figure 13):

- **Define material requirements** which consist of a broad range of material properties, as shown in Figure 13, and have to be defined by companies according to prototypes, tools, and the products they want to produce.

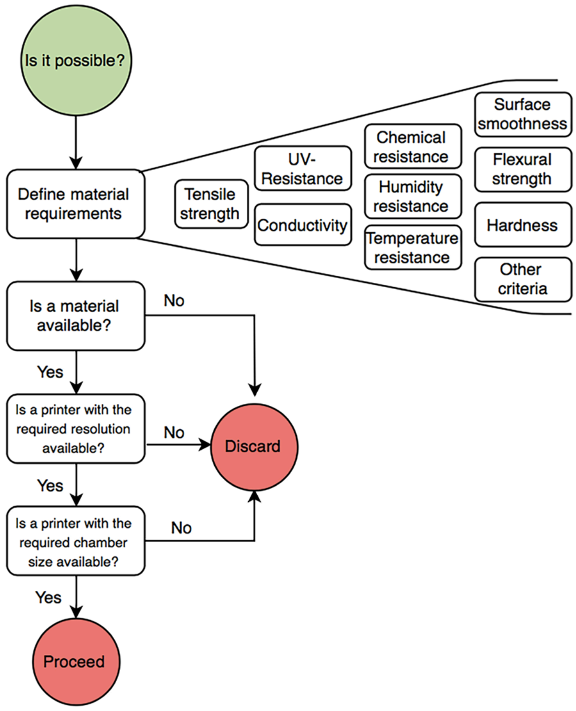


Figure 13: A process model for possibility analysis.

- **Is the material available (material availability)** to meet the requirements defined by companies? If these are not fulfilled, companies should discard the intention of using AM in the specific case. However, if there is a material available, they can proceed to the next step.

- **Is a printer available (printer availability)** to meet the requirements regarding resolution (related to the smallest feature size and minimum layer height) and chamber size, etc. (Figure 13 only includes these two requirements, but there can be more according to the needs of companies)? If not, the intention of using AM for the specific case must be discarded. If a printer is available, companies can proceed to the profitability analysis.

To some extent, materials, AM technologies, and printers are interrelated, and AM technologies are compatible with different materials and printers. This means that once materials are chosen, AM technologies that can be adopted are determined, and printers can be selected accordingly from a range of limited options. Figure 14 is developed to summarise the most common plastic and metal materials used for AM as well as their corresponding AM technologies. Besides, *two excel tools* are developed to facilitate the understandings of materials and printers as well as helping to make the right choices. Other processes of selecting the right AM technologies/printers can also be seen on 3D Hubs (2021c; 2021d).

download Technology and material tool

download Printer selection tool

Material		Application	Corresponding AM Technology	Strengths & Weaknesses of AM Technology	Characteristics of AM Technology
Thermoplastics	PLA	The most common and low-cost AM plastic. Ideal for non-functional prototyping with sharp details. Unsuitable for high temperatures.	**FDM** is the most widely available 3D printing process, mainly used for low-cost prototyping and design verification with very fast turnaround times.	**Strengths:** Low-cost, fast turnaround times. **Weaknesses:** Limited dimensional accuracy, print layers are likely to be visible.	**Price:** Low **Lead time:** < 2 days **Wall thickness:** 0.8 mm **Tolerances:** ± 0.5% (min: ± 0.5 mm) **Max part size:** 100 x 100 x 100 cm **Layer height:** 50-400 µm
	ABS	A commodity plastic with better mechanical and thermal properties compared to PLA and excellent impact strength.			
	PETG	An easy-to-print plastic with high impact strength and excellent chemical and moisture resistance.			
	ASA	Mechanical properties similar to ABS, with improved printability, UV stability, and high chemical resistance. Commonly used for outdoor applications.			
	PEI (ULTEM)	An engineering thermoplastic with good mechanical properties and exceptional heat, chemical, and flame resistance.			
	TPU	A thermoplastic elastomer with low hardness and a rubber-like feel that can be easily flexed and compressed.	**SLS** is used for both prototyping and small-batch production of functional plastic parts with good mechanical properties.	**Strengths:** No support material required, excellent mechanical properties, can produce complex geometries. **Weaknesses:** Higher cost than FDM, longer lead times than FDM.	**Price:** Relatively high **Lead time:** < 5 days **Wall thickness:** 0.7 mm **Tolerances:** ± 0.3% (min: ± 0.3 mm) **Max part size:** 75 x 55 x 55 cm **Layer height:** 80-120 µm
	Nylon	A plastic with excellent mechanical properties and high chemical and abrasion resistance. Perfect for functional applications.			
Thermosets	Resin	Thermoset polymers that produce high detail parts with a smooth, injection mold-like surface. Ideal for prototyping.	**SLA** is most suitable for visual applications where a smooth, injection mold-like surface finish and a high level of feature detail are required.	**Strengths:** Fine features & high detail, smooth, injection mold-like surface finish. **Weaknesses:** Support marks may be visible on surface, brittle, not recommended for functional parts.	**Price:** Relatively low **Lead time:** < 2 days **Wall thickness:** 0.5 mm **Tolerances:** ± 0.5% (min: ± 0.15 mm) **Max part size:** 150 x 75 x 50 cm **Layer height:** 25-100 µm
Metal	Stainless steel	A metal alloy with high ductility and high wear and corrosion resistance that can be easily welded, machined, and polished.	**DMLS/SLM** produce high performance, end-use metal 3D printed parts for industrial applications within the aerospace, automotive, and medical industries.	**Strengths:** Excellent mechanical properties, can produce complex geometries. **Weaknesses:** High cost.	**Price:** High **Lead time:** < 10 days **Wall thickness:** 0.4 mm **Tolerances:** ± 0.1 mm **Max part size:** 50 x 28 x 36 cm **Layer height:** 30-50 µm
	Aluminium	A metal with good strength-to-weight ratio, high thermal and electrical conductivity, low density, and natural weather resistance.			
	Titanium	A metal with an excellent strength-to-weight ratio, low thermal expansion, and high corrosion resistance that is sterilisable and biocompatible.			
	Cobalt-chrome	A metal super-alloy with excellent strength and outstanding corrosion, wear, and temperature resistance.			
	Nickel alloys	Excellent strength and fatigue resistance. Can be used permanently at temperatures above 600 °C.			
Other	Sand	Very low elongation at break, high stiffness, full colour presentation models, excellent for sand casting application.	**Binder Jetting** is a flexible technology with diverse application, ranging from low-cost metal 3D printing to full-colour prototyping and large sandcasting mold production.	**Strengths:** Low cost, full colour prototyping, very large printing capabilities. **Weaknesses:** Inferior material properties, design restrictions due to post-processing, fine details not printable.	**Price:** Relatively low **Wall thickness:** 0.4 mm **Tolerances:** ± 0.3 mm **Max part size:** 180 x 100 x 70 cm **Layer height:** 100 µm
	Composites	High stiffness, good strength-to-weight ratio, wear resistance.	FDM and SLS	See above	See above

Figure 14: *A summary of the most common plastic and metal materials used for AM as well as their corresponding AM technologies (adopted from 3D Hubs, 2021c).*

2.4 Multi Criteria Decision Making (MCDM)

However, no matter whether companies follow a top-down or a bottom-up approach, companies might still end up with many options that hold the possibility to be AM'ed. With all these options, it can be too time-consuming to conduct a profitability analysis for each of them. In this case, companies can use Multi Criteria Decision Making (MCDM) to help themselves finding the most suitable prototypes, tools, or products among those 'passing' the possibility analysis for AM (Chen & Hwang, 1992). This method includes five steps (see Figure 15):

- **Define alternative criteria to be examined:** It is suggested in Figure 12 to take four criteria, i.e., demand variation, volume, criticality (lead time), and total cost, into consideration as they are quantitively measurable.

- **Define weights:** Companies need to allocate the weights for four criteria (0-1, the sum should be 1) according to their importance.

- **Plot values of criteria:** Companies review their operations and provide average values (e.g., per month) of the four criteria regarding prototypes, tools, or products that pass the possibility analysis.

- **Examine results:** *An excel tool* is developed to execute MCDM specifically based on the TOPSIS method. Companies can simply input the weights of the four criteria, as well as the values of the four criteria regarding prototypes, tools, and products that 'pass' the possibility analysis. Based on these inputs, the excel tool will return with the ranking of prototypes, tools, or products, in terms of their suitability for AM.
  download MCDM tool

- **Make solid decision:** Companies can then choose which prototypes, tools, or products proceed to the next step, i.e., profitability analysis.

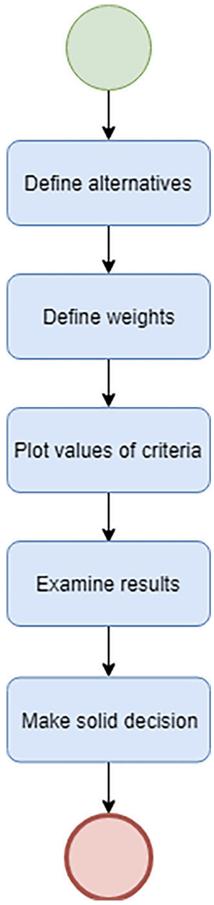


Figure 15: MCDM process

2.5 Question 3 (Profitability Analysis): Whether it is Economically Better to Use AM in Operations?

The last question of AM adoption is concerned with whether it is profitable for companies to use AM for producing specific prototypes, tools and/or products. In order to answer this question, the economic and operational analyses will be conducted based on three criteria, i.e., volume, criticality (lead time), and total cost, for the purpose of developing business cases, as suggested in Figure 12. Essentially, companies need to compare three criteria in terms of three scenarios:

- **Current:** Producing with traditional manufacturing technologies.

- **Internal:** Buying printers and producing internally.

- **External:** Using external services for AM.

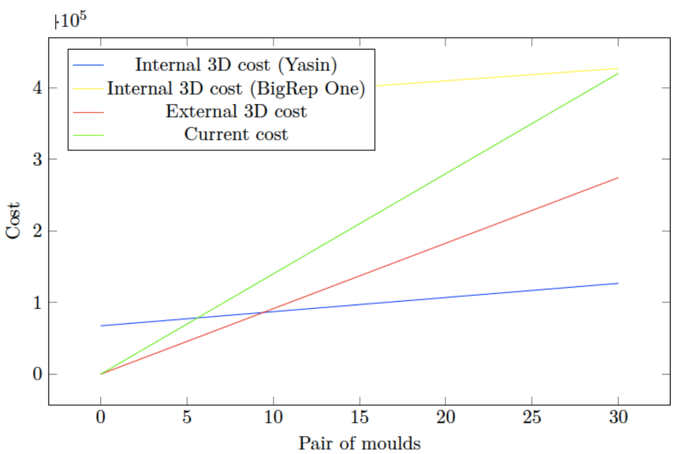
Corresponding to these scenarios, the process of the economic and operational analyses includes the following steps:

- In terms of different scenarios, identify cost types (e.g., salary, material power, machine, maintenance, etc.) and create *case-specific* cost structures/models by considering adopting AM in which applicationsto ; a lifecycle perspective should be adopted here.

- In terms of different scenarios, identify lead time types (e.g., developing time, production time, transportation time, etc.) and create *case-specific* lead time structures/models by considering adopting AM in which applicationsto .

- Gather the data of the identified cost and lead time types and input them into cost and lead time structures/models for the calculations of total cost and lead time. The calculations should be made for individual prototypes, tools, or products, but it should be noticed that the cost of buying printers can be shared among prototypes, tools, or products with similar requirements when calculating total costs.

- For individual prototypes, tools, or products, companies need to compare their total costs and lead times in terms of three scenarios, in order to decide which ones that are profitable to be produced by AM. In most cases, such a decision is also dependent on the volume to be produced, especially regarding total costs. Thus, a figure (similar to Figure 16) can be drawn to make this decision more intuitive. Besides, a trade-off might have to be made between cost and lead time depending on situations faced by companies.



Scenario	1st Priority	2nd Priority	Volume
External	Cost	Lead time	<10
Internal using Yasin	Cost	Lead time	10-1231
Internal using BigRep One	Cost	Lead time	>1231

Figure 16: *A figure to facilitate profitability analysis.*

After these steps, companies will be able to choose which prototypes, tools, or products that are possible and profitable to be produced by AM for specific applications (i.e., rapid prototyping, rapid tooling, or rapid manufacturing).

2.6 Strategic Matrix

After the possibility and profitability analyses, it might be found that no prototype, tool, or product is suitable for AM. Even though, it may still be beneficial for companies to adopt AM due to various strategic reasons, e.g., companies might like to learn more about AM by getting more hands-on experience to prepare for the future. Thus, it is suggested that companies can apply the *Strategic Matrix* method to evaluate other qualitative but strategic criteria, including geometric complexity and supply risk (see Figure 12), in terms of their strategic importance. This method is illustrated in Figure 17 by considering geometric complexity and supply risk as two example dimensions (Knofius et al., 2016).

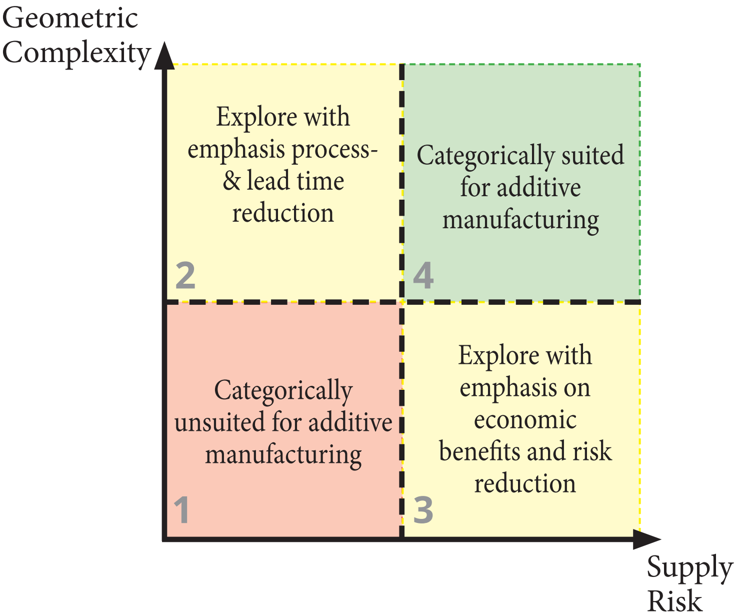


Figure 17: *Strategic Matrix method.*

Prototypes, tools, and products found in Field 1, which is characterised by low geometric complexity and low supply risk, can be deemed unsuited for AM. Those in Field 2, with high geometric complexity and low supply risk, often result in a complex manufacturing process. Companies can pursue AM if process and lead time are critical. Those found in Field 3, where geometric complexity is low and supply risk is high, can be pursued for AM if the supply risk and associated costs are critical. Those found in Field 4, where both geometric complexity and supply risk are high, are highly suited for AM, which is the best suited case to potentially be manufactured by AM. However, it should be noticed that Figure 17 is just an example regarding how to use the strategic matrix. The essence of this method is to classify prototypes, tools, and products in terms of their importance for chosen strategic aspects and then select the suitable ones for AM. The matrix can be 2 by 2, 3 by 3, or even more.

3. Where to Start the Adoption of AM

The adoption of AM is not simple. It would be a good idea for companies to start out with some easy tasks and gradually extend the scope of the AM adoption in their operations. More specifically, they can follow the tips below in order.

3.1 Buy a Cheap Printer and Play

Although it is not enough to establish an overview of AM based on one single type of printer, companies can simulate the enthusiasm of their employees about AM by buying a cheap printer and allowing employees to 'play' with it. Driven by their interest, employees are expected to accumulate more basic knowledge on AM, such as the capabilities, strengths, and limitations of current AM technologies. There are extensive resources online regarding AM technologies which can be used as education materials, e.g., 3dhubs.com. Besides, companies should also provide support, e.g., paying for courses, if employees would like to know more about AM.

3.2 Run a Pilot Project, but Analyse Before Investment

The best way to convince someone is to show them the results. Companies can follow the processes and methods described in chapter 2 of this guidebook to identify potential pilot projects and develop business cases. At this stage, it is not recommended for companies to invest in AM printers, unless they really find a range of prototypes, tools, and products that can be produced by a single printer. Instead, they should try to use the printer bought in the first step mentioned above or simply turn to an AM service provider, which is the next tip.

3.3 Use an External AM Service Provider at the Early Stage

In fact, it is not uncommon for companies, especially small businesses, to outsource their AM needs to an AM service provider. Even if the cost of the equipment is within budget, the time required to operate and maintain a printer can occupy precious engineering resources. Using an AM service provider allows companies to take advantage of the full benefits of 3D printing, while focusing on developing their own products. Besides, by buying a printer, companies commit to a specific AM technology and a limited set of materials. However, the AM landscape is continuously evolving. What works best for a company today might not meet the requirements of tomorrow. In this case, using an AM service provider also allows companies to stay flexible while having an easy access to the latest technologies.

3.4 Upscale the Adoption of AM in Operations

After proving that AM can add value to companies, the next step would be to upscale the activities in this area in the following steps:

- **Supporting internal operations:** In this step, companies need to consider how to use AM to support their internal operations to become more successful without making significant changes on e.g. the product or the supply chain. Rapid prototyping during the design phase or manufacturing of custom tooling are two options that many businesses have achieved great success. Besides, AM also allows the production of more customised products as well as the elimination of assembly lines for many products.

- **Redesigning products:** In this step, companies might like to re-design their products in order to get the most out of AM adoption as AM stimulates more new designs with functional integration and without geometry limitation. A solution is to create structures with a form that is optimised for the functional requirements of the applications. These optimised structures are typically economically unfeasible to manufacture within traditional methods.

- **Reconsidering supply chains:** In this step, companies might like to even reconsider their supply chain setups. The ability to manufacture parts where you need them and when you need them is one of the key strengths of AM. Thus, it is probably not a surprise that spare part production is becoming one of the mainstream applications. AM allows spare parts to be produced at warehouses near by or even at specific service locations. In doing so, companies can dramatically reduce the tiers of their supply chains and further their inventory and transportation costs while shortening delivery time. This also implies that reconsidering the configuration of the supply chain is a must (Li et al., 2019).

- **Redeveloping business models:** In this step, companies might even like to redevelop their business models. The adoption of AM brings companies diversified possibilities to offer their customers more customised products and/or even services. Thus, companies might like to shift from a manufacturer to a service provider based on the customised products made from AM.

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