Module 1

Introduction to Additive Manufacturing: Introduction to AM, AM evolution, Distinction between AM & CNC machining, Advantages of AM,

AM process chain: Conceptualization, CAD, conversion to STL, Transfer to AM, STL file manipulation, Machine setup, build , removal and clean up, post processing.

Classification of AM processes: Liquid polymer system, Discrete particle system, Molten material systems and Solid sheet system.

Post processing of AM parts: Support material removal, surface texture improvement, accuracy improvement, aesthetic improvement, preparation for use as a pattern, property enhancements using non-thermal and thermal techniques.

Guidelines for process selection: Introduction, selection methods for a part, challenges of selection

AM Applications: Functional models, Pattern for investment and vacuum casting, Medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Re-manufacturing. Application examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

Introduction to AM

Additive Manufacturing

The term 'additive manufacturing' was given by the ASTM F42 committee.

- Technology that can make anything.
- Eliminates many constraints imposed by conventional manufacturing
- Leads to more market opportunities.

Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material.

The term **'3D printing'** is increasingly used as a synonym for AM. However, the latter is more accurate in that it describes a professional production technique which is clearly distinguished from conventional methods of material removal.

Additive manufacturing, also known as 3D printing, rapid prototyping or freeform fabrication, is 'the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies' such as machining.

The use of Additive Manufacturing (AM) with metal powders is a new and growing industry sector with many of its leading companies based in Europe. It became a suitable process to produce complex metal net shape parts, and not only prototypes, as before.

Additive manufacturing now enables both a design and industrial revolution, in various industrial sectors such as aerospace, energy, automotive, medical, tooling and consumer goods.

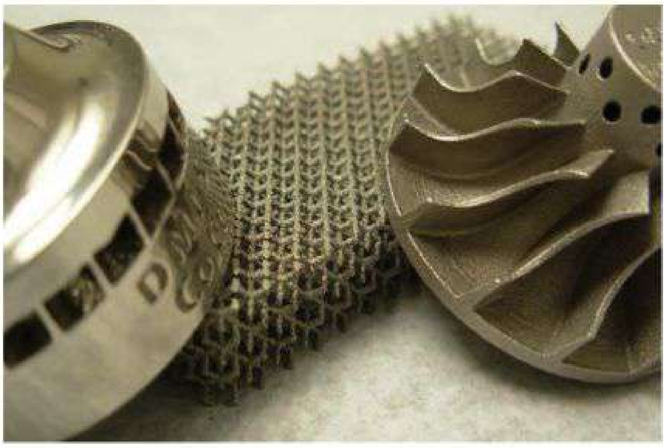


Photo: Examples of direct metal laser sintering

Photo: Selective laser sintered (SLS)

AM evolution

- In the 60s Herbert Voelcker had thoughts of the possibilities of using computer aided machine control to run machines that build parts from CAD geometry.
- In the 70s he developed the mathematics to describe 3D aspects that resulted in the first algorithms for solid modeling
- in the 80s Carl Deckard came up with the idea of layer-based manufacturing
- And while there are several people that have pioneered the Rapid Prototyping technology, the industry generally gives credit to Charles Hull.

Additive manufacturing first emerged in 1987 with stereolithography (SL) from 3D Systems, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser. The SLA-1, the first commercially available AM system in the world, was the precursor of the once popular SLA 250 machine. (SLA stands for StereoLithography Apparatus.) The Viper SLA product from 3D Systems replaced the SLA 250 many years ago.

In 1988, 3D Systems and Ciba-Geigy partnered in SL materials development and commercialized the first-generation acrylate resins. DuPont's Somos stereolithography machine and materials were developed the same year. Loctite also entered the SL resin business in the late 1980s, but remained in the industry only until 1993.

After 3D Systems commercialized SL in the U.S., Japan's NTT Data CMET and Sony/D-MEC commercialized versions of stereolithography in 1988and 1989, respectively. NTT Data CMET (now a part of Teijin Seiki, a subsidiary of Nabtesco) called its system Solid Object Ultraviolet Plotter (SOUP), while Sony/D-MEC (now D-MEC) called its product Solid Creation System (SCS). Sony stopped manufacturing SL systems for D-MEC in 2007.

In 1988, Asahi Denka Kogyo introduced the first epoxy resin for the CMET SL machine. The following year, Japan Synthetic Rubber (now JSR Corp.) and DSM Desotech began to offer resins for the Sony/D-MEC machines.

In 1990, Electro Optical Systems (EOS) of Germany sold its first Stereos stereolithography system. The same year, Quadrax introduced the Mark 1000 SL system, which used visible light resin. The following year, Imperial Chemical Industries introduced a visible light resin product for use with the Mark 1000. ICI stopped selling its resin about one year later when Quadrax dissolved due to a legal conflict with 3D Systems.

In 1991, three AM technologies were commercialized, including fused deposition modeling (FDM) from Stratasys, solid ground curing (SGC) from Cubital, and laminated object manufacturing (LOM) from Helisys.

Selective laser sintering (SLS) from DTM (now a part of 3D Systems) and the Soliform stereolithography system from Teijin Seiki became available in 1992.

In 1993, Soligen commercialized direct shell production casting (DSPC). Using an inkjet mechanism, DSPC deposited liquid binder onto ceramic powder to form shells for use in the investment-casting process.

1994 was a year of many new additive-manufacturing system introductions. ModelMaker from Solidscape (then called Sanders Prototype) became available, as did new systems from Japanese and European companies.

In 1996, Stratasys introduced the Genisys machine, which used an extrusion process similar to FDM but based on technology developed at IBM's Watson Research Center.

In 1998, Beijing Yinhua Laser Rapid Prototypes Making & Mould Technology Co., Ltd. stepped up the promotion of its products.

In March 1999, 3D Systems introduced a faster and less expensive version of Actua 2100 called ThermoJet

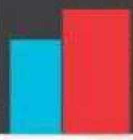
In January 2000, Helisys announced that Toyoda Machine Works of Japan would manufacture and sell LOM systems in Japan.

The evolution of additive manufacturing

For the past few decades, additive manufacturing (AM) has developed from rapid prototyping using simple 3D printers to a complex manufacturing technology that enables the production of functional finished components. Additive manufacturing is evolving due in part to the expanding number of materials that are now being explored and used, such as composites, ceramics, and metal alloys. While a greater number of manufacturers are adopting AM technologies as they have become more commercially viable and more and more materials can be used, many still view it as simply a tool for rapid prototyping.

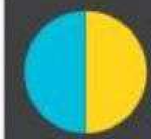
AT A CROSSROADS

Additive manufacturing is growing rapidly



The industry grew by 35.2% last year, according to Wohlers Report 2015[1]

but, according to a survey of 100 industrial manufacturers:



Over 50% are merely experimenting with 3D printing or using it for rapid prototyping only[2]

signaling the continuing potential for AM to revolutionize manufacturing as we know it today

1988-1994	rapid prototyping
1994	rapid casting
1995	rapid tooling
2001	AM for automotive
2004	aerospace (polymers)
2005	medical (polymer jigs and guides)
2009	medical implants (metals)
2011	aerospace (metals)
2013-2016	nano-manufacturing
2013-2017	architecture
2013-2018	biomedical implants
2013-2022	in situ bio-manufacturing
2013-2032	full body organs

Distinction between AM & CNC machining

CNC machining and additive manufacturing are both computer-controlled solutions to making products out of a given material. They're both machines at the forefront of building technology safely and efficiently.

As machinists and engineers want to build a prototype, a part or a custom product, they can turn to one of these machines to do the job for them. As long as the machines have the design, you don't have to worry about human error because the machines are automated. While this doesn't mean issues don't arise, there's more consistency with production and less chance of injury.

There is some overlap with these two manufacturing methods. Some CNC machines can use STL and OBJ files, which 3D printers also accept.

CNC machinery is older than 3D printing and still has a stronger foothold in manufacturing. The form started in the 1940s and had molded to fit into the industry up to the present. 3D printing came along in 1986. It's still relatively new and evolving to be more accessible and versatile. 3D printing can help in some areas of prototyping, but it's not a replacement tool for CNC machining.

They're not so much alternatives to the other as they are both aspects of the manufacturing world. They meet different demands and handle different materials and markets. CNC machines and 3D printing both have unique capabilities and constraints that suit them for specific jobs. As they fit their niches in the market, you'll want to compare it to whatever industry you're in.

3D printers are typically more efficient than traditional manufacturing. The printer uses the materials that make up the item it's creating, whereas traditional manufacturing methods such as CNC Machining require more materials for the mold to work. On average, 3D printers produce less waste than traditional manufacturing methods.

However, when production is large-scale, traditional manufacturing methods have a distinct advantage. Assembly lines are faster than a 3D printer in mass production because printers build layer by layer. In the hours that it could take to 3D print a product, an assembly line could have mass-produced hundreds of the same product.

Additionally, 3D printers can only use the area of the printing bed for making parts. Large-scale parts might not fit in that space. While the parts can be broken down into smaller pieces 3D printers can build, that might not be cost-effective and will take time. Traditional manufacturing has the advantage of the assembly line's labor and will be able to produce items on a larger scale. Future 3D printers could be able to build larger items, but not on the level of what CNC machines offer with regard to quality and quantity.

3D printers can manipulate different materials such as plastics, metals and polymers. However:

- Not all 3D printers can use these materials. It takes separate machines for each material.
- 3D printers cannot work with every material that traditional manufacturers use due to high melting points.

- Some projects might not be able to consider using 3D printers if they require specific materials that are incompatible with the printers.

3D Printing vs. Traditional Manufacturing

CNC machining starts with a block of material and shapes it with a rotating tool. Following the program, it carves away excess until you have the finished product. This is the subtractive method because it's taking away material.

3D printing layers on material in the additive method that builds your design. Both ways have pros and cons in terms of durability, precision and use of materials.

Material Usage for CNC and 3D

CNC machining works with a variety of materials. They can use:

- Metal alloys
- Woods
- Acrylic
- Modeling foam
- Thermoplastics
- Machining wax

CNC machines have heating systems that can manage heavy materials. These materials are used to build substantial parts for engines, aircraft and other machines. They need to be exact, dependable and durable. The cutting tools for the design might have to switch, but most tools are standardized to fit any CNC machine.

3D printing doesn't have this variety, using materials like plastics or resins. They can't produce items strong enough to withstand intense environments like airplanes or other machinery. Also, 3D printers can't switch between materials. Certain 3D printers are for specific kinds of material.

3D and CNC Precision of Production

CNC machining is more precise and consistent than 3D printing because they have a higher tolerance for heat. 3D printers end up with distorted products when there's too much heat. They can offer precision but cannot remain consistent. 3D printers are often regarded as more user-friendly than CNC machines, but when they malfunction, someone has to troubleshoot them because the fault means production of unusable products.

CNC and 3D Speed of Production

CNC is a faster solution than 3D printing. Automated CNC machines can work around the clock as long as they're properly maintained. A project that could take CNC machining an hour would equate to a 3D printer taking hours to get the final product because it has to build the product layer by layer. A 3D printer's pace might have to slow down during the process to get the design right. Different 3D printers could also be programmed with specific speeds that you can't alter. It depends on the machine you use.

3D printed products also require work after they're built. The products need to be washed, polished and sealed before people can use the product. This could extend prototype testing to a longer time period with a lot of waiting in between. 3D printers are also popular for smaller, custom-manufactured items. But if you have to wait for the item to be built and still do a lot of work post-print, you lose a lot of time before you can move the product.

Versatility of Machinery for CNC vs. 3D

CNC machines can produce fixtures, tools and custom-designed parts. They have a wide range of quality settings so you can make a prototype that has a rougher design in some areas and perfect in others so you can test that part.

When testing prototypes for a project, a CNC machine could quickly build a design so the developers can test it. 3D printers don't have these kinds of options. It will slowly shape the design as it was programmed. Accuracy is key when constructing a final product, but when time is a constraint and you want to test some prototypes, 3D printers can slow down you and your project. Designs made for a CNC machine usually can't be substituted with a 3D printer because the products are voluminous and it would take hours for a 3D printer to finish them.

Noise and Mess Produced by CNC and 3D

These differences relate to the subtractive and additive methods. CNC machining is much noisier and messier than 3D printing because it uses a tool to cut away material. This creates noise and a lot of scrap metal or wood shavings. CNC machines cause a lot of vibrations, so they need to be in a space where they won't bother anyone. 3D printing only uses the material it needs for the product. There's little to no waste, and the printers don't vibrate like a CNC machine.

Advantages of AM

- Increased design freedom versus conventional casting and machining
- Light weight structures, made possible either by the use of lattice design or by designing parts where material is only where it needs to be, without other constraints
- New functions such as complex internal channels or several parts built in one
- Net shape process meaning less raw material consumption, up to 25 times less versus machining, important in the case of expensive or difficult to machine alloys. The net shape capability helps creating complex parts in one step only thus reducing the number of assembly operations such as welding, brazing.
- No tools needed, unlike other conventional metallurgy processes which require molds and metal forming or removal tools
- Short production cycle time: complex parts can be produced layer by layer in a few hours in additive machines. The total cycle time including post processing usually amounts to a few days or weeks and it is usually much shorter than conventional metallurgy processes which often require production cycles of several months.

AM process chain

A series of steps goes into the process chain required to generate a useful physical part from the concept of the same part using additive manufacturing processes. Depending on the technology and, at times the machines and components, the process chain is mainly made up of six steps:

• Generation of CAD model of the design;
• Conversion of CAD model into AM machine acceptable format;
• CAD model preparation;
• Machine setup;
• Part removal; • Post-processing.

These steps can be grouped or broken down and can look different from case to case, but overall the process chain from one technology remains similar to that of a different technology. The process chain is also constantly evolving and can change as the existing technologies develop and new technologies surface.

Generation of Computer-Aided Design Model of Design

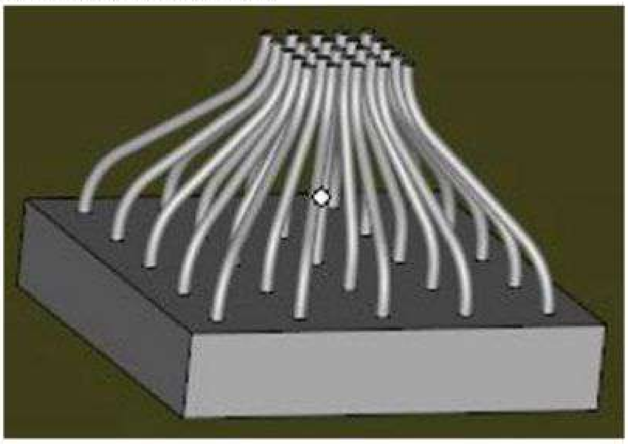
In terms of process chain, the first enabler of AM technologies is 3D digital Computer-Aided Design (CAD) models where the conceptualized product exist in a "computer" space and the values of its geometry, material, and properties are stored in digital form and are readily retrievable.

In general, the AM process chains start with 3D CAD modeling. The process of producing a 3D CAD model from an idea in the designer's mind can take on many forms, but all requires CAD software programs. There are a large number of CAD programs with different modeling principles, capabilities, accessibilities, and cost. Some examples includes Autodesk Inventor, Solidworks, Creo, NX, etc.

Once a 3D CAD model is produced, the steps in the AM process chain can take place. Though the process chain typically progresses in one direction that starts with CAD modeling and ends with a finished part or prototype, it is often an iterative process where changes to the CAD model and design are made to reflect feedback from each steps of the process chain.

Conversion of CAD Model into AM Machine Acceptable Format

Almost all AM technology available today uses the STereoLithography (STL) file format. Shown in below Fig. is an example part in its STL format.



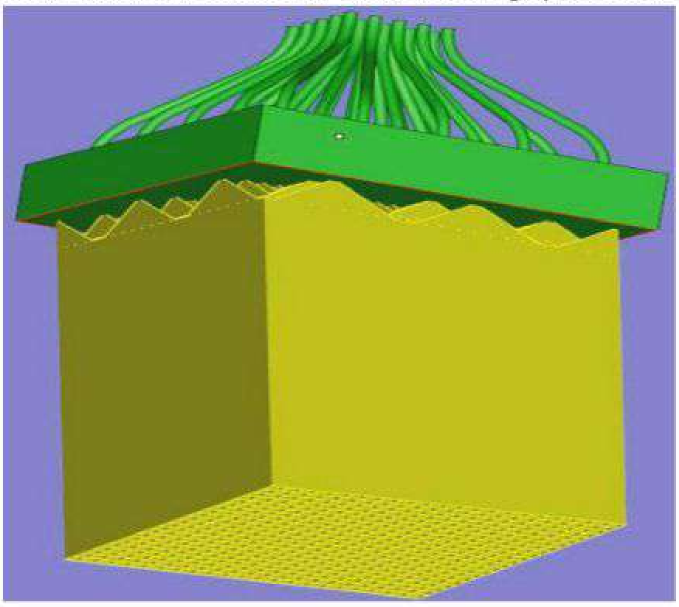
The STL format of a 3D CAD model captures all surfaces of the 3D model by means of stitching triangles of various sizes on its surfaces. The spatial locations of the vertices of each triangle and the vectors normal to each triangle, when combined, these features allow AM pre-process programs to determine the spatial locations of surfaces of the part in a build envelope, and on which side of the surface is the interior of the part.

STL format has been consider the de facto standard, it has limitations intrinsic to the fact that only geometry information is stored in these files while all other information that a CAD model can contain is eliminated. Information such as unit, color, material, etc. can play critical role in the functionality of the built part is lost through the file translation process.

The "AMF" format was developed specifically to address these issues and limitations, and is now the ASTM/ISO standard format. Beyond geometry information, it also contains dimensions, color, material, and additional information is also possible with this file format. Though currently the predominate format of file used by AM systems and supported by CAD modeling programs is still the STL format.

CAD Model Preparation

Once a correct STL file is available, a series of steps is required to generate the information an AM system needs to start the build process. The needed information varies, depending on the technology but in general these steps start with repairing any errors within the STL file. Typical errors can be gaps between surface triangle facets, inverted normal where the "wrong side" of a triangle facet is identified as the interior of the part. Once the errors have been repaired, a proper orientation of the 3D model with respect to the build platform/envelope is then decided. Following the orientation, the geometry, density, geometry of support structures are decided and generated in 3D model space and assigned to the part model. The process then progresses to slicing the 3D model defined by the STL as well the support structure into a given number of layers of a desired height each representing a slice of the part and support models. Within each slice the cross-sectional geometry is kept constant.
STL file has been processed and machine specific information to allow placement of the material unit into the desired location in a controlled manner to construct the physical model layer by layer.



Support structure generated on the model

STL file is first imported into a software that allows repairing and manipulating of the file, as well as the generation of support, and the slicing of the part and support models. The sliced data are then transferred into the AM system machine for build preparation and the start of the building process. There are a number of software programs that allows these tasks to be carried out, Magics, for example by **Materialise is one such software program** that is capable of integrating all CAD model preparation steps into one program and generating data files directly accepted by machine systems.

STL File Preparation

The CAD model preparation starts with importing an STL, or other compatible file formats, into the pre-process software program (e.g., Magics). Once imported, the dimensions can be modified if needed. Once the model is in desired dimensions, a series of steps is carried out to correct possible errors in the model file. These errors can include missing triangles, inverted or double triangles, transverse triangles, open edges and contours, and shells. Each type of error can cause issues in the building process or result in incorrect parts and geometries. While some errors such as shells and double triangles are non-critical and can sometimes be tolerated, errors such as inverted triangles and open contours can cause critical issue in the building process and needs to be resolved during STL preparation.

Support Generation

Generation of support structures can be accomplished in a few different ways. Also applied to any other AM processes, the first way is to generate the support structures during CAD modeling and design the support to be features of the geometry of the part. Alternatively, the support structures can be generated in the STL preprocess software program. This second approach provides much more flexibility in terms of being able to tailor the structures based on the detailed needs.

Build File Preparation

Once the CAD models of part and support are generated and prepared in the pre-process software program, a slicer program is used to divide the models into layers in the build direction based on the desired layer thickness.

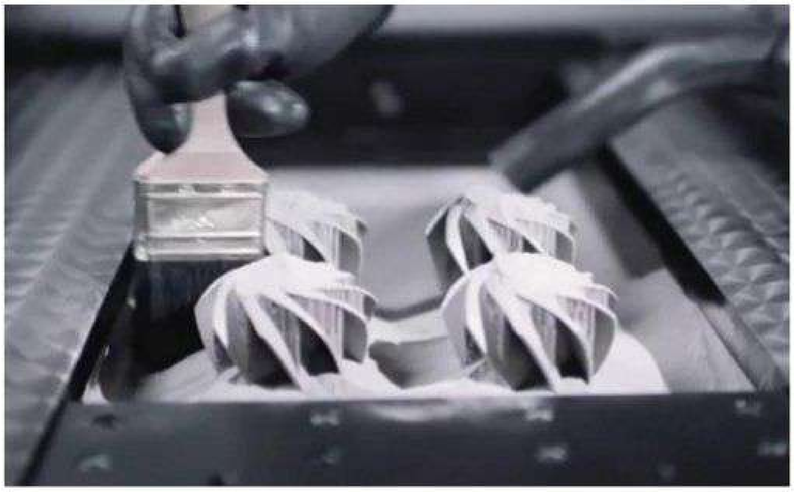
Machine Setup

Following software preparation steps in the AM process chain, machine preparation is the next step before a build a can start. Machine preparation can roughly be divided into two groups of tasks: **machine hardware setup, and process control.**

Hardware setup entails cleaning of build chamber from previous build, loading of powder material, a routine check of all critical build settings and **process controls** such as gas pressure, flow rate, oxygen sensors, etc. Details of how each task in this group is carried out can vary from one system to another, but overall once the machine hardware setup is complete, the AM system is ready to accept the build files (slices generated from previous step) and start the build.

Build Removal

The build time of the powder bed process depends on a number of factors. Of them, the height of the entire build has the largest effect on the total time. It can take anywhere from minutes to days. Nevertheless, once the build completes, the laser metal powder bed technology allows for immediate unpacking of build chamber and retrieval of finished part, because the process does not maintain the build platform at elevated temperatures (as opposed to laser powder bed for polymers and electron beam-based powder bed processes). The unpacking process typically involves raising the platform in the build chamber and removing loose powder at the same time. The loose powder from one process can be re-used and has to go through a series of sieving steps to remove contaminates and unwanted particulates.



SLM part being extracted from build chamber

Post-processing

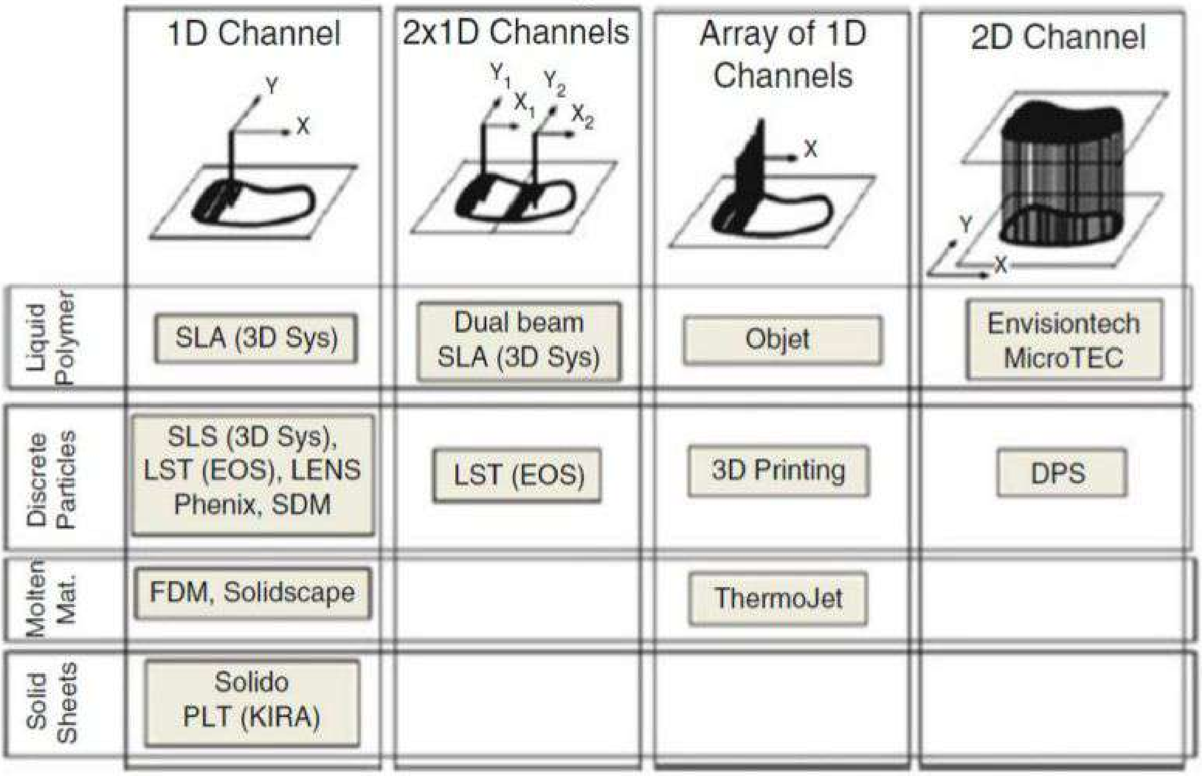
Depending on AM technology used to create the part, the purpose, and requirements of the finished part, the post-fabrication processes can vary in a wide range. It can require anything from no post process to several additional steps of processing to change the surface, dimensions, and/or material properties of the built part.

Ex: In metal powder bed AM systems, the minimum required processing is removal of built part from build plate and the removal of support structures from the built part. Removal of support structures can be as simple as manually breaking the supports from the surface of the part, but it can also be a process that utilizes CNC tools to not only remove the support, but also to achieve desired surface finish and/or dimension tolerance.

Classification of AM Processes

There are numerous ways to classify AM technologies. A popular approach is to classify **according to baseline technology**, like whether the process uses lasers, printer technology, extrusion technology, etc. Another approach is to collect processes together according to the **type of raw material input**. The problem with these classification methods is that some processes get lumped together in what seems to be odd combinations (like Selective Laser Sintering (SLS) being grouped together with 3D Printing) or that some processes that may appear to produce similar results end up being separated (like Stereolithography and material jetting with photopolymers). It is probably inappropriate, therefore, to use a single classification approach.

An excellent and comprehensive classification method is described by Pham, which uses a two-dimensional classification method as shown in Fig.



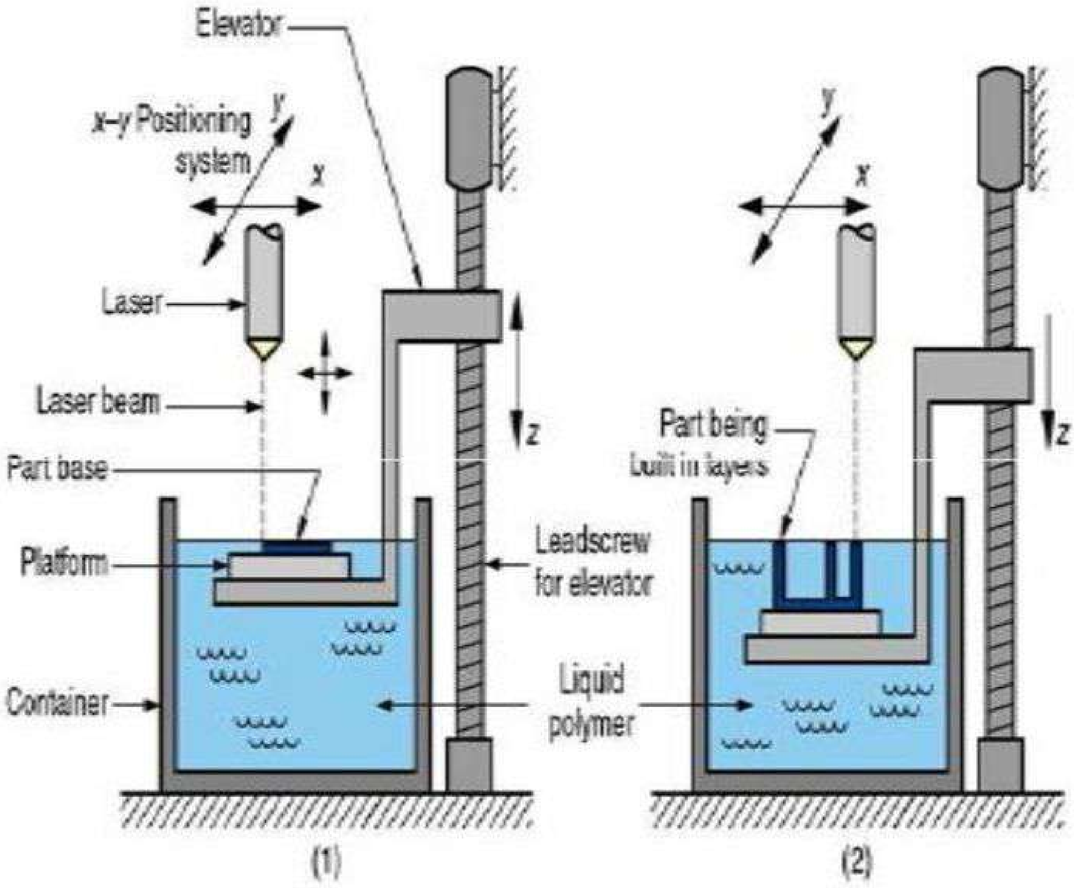
<u>Liquid Polymer Systems</u>

The first commercial system was the 3D Systems Stereolithography process based on liquid photopolymers. A large portion of systems in use today are, in fact, not just liquid polymer systems but more specifically liquid photopolymer systems. However, this classification should not be restricted to just photopolymers, since a number of experimental systems are using hydrogels that would also fit into this category.

Using this material and a 1D channel or 2X1D channel scanning method, the best option is to use a laser like in the Stereolithography process. Droplet deposition of polymers using an array of 1D channels can simplify the curing process to a floodlight (for photopolymers) or similar method.

Stereolithography

- One of the most important additive manufacturing technologies currently available.
- The first ever commercial RP systems were resin-based systems commonly called stereolithography or SLA.
- The resin is a liquid photosensitive polymer that cures or hardens Stereolithography when exposed to ultraviolet radiation.
- This technique involves the curing or solidification of a liquid photosensitive polymer through the use of the irradiation light source.
- The source supplies the energy that is needed to induce a chemical reaction (curing reaction), bonding large no of small molecules and forming a highly cross-linked polymer.
- The UV light comes from a laser, which is controlled to scan across the surface according to the cross-section of the part that corresponds to the layer.
- The laser penetrates into the resin for a short distance that corresponds to the layer thickness.
- The first layer is bonded to a platform, which is placed just below the surface of the resin container.
- The platform lowers by one-layer thickness and the scanning is performed for the next layer. This process continues until the part has been completed.



Discrete Particle Systems

Discrete particles are normally powders that are generally graded into a relatively uniform particle size and shape and narrow size distribution. The finer the particles the better, but there will be problems if the dimensions get too small in terms of controlling the distribution and dispersion. Again, the conventional 1D channel approach is to use a laser, this time to produce thermal energy in a controlled manner and, therefore, raise the temperature sufficiently to melt the powder.

Polymer powders must therefore exhibit thermoplastic behavior so that they can be melted and re-melted to permit bonding of one layer to another. There are a wide variety of such systems that generally differ in terms of the material that can be processed.

The two main polymer-based systems commercially available are the SLS technology marketed by 3D Systems and the EOSint processes developed by the German company EOS.

Application of printer technology to powder beds resulted in the (original) 3D Printing (3DP) process. This technique was developed by researchers at MIT in the USA. Droplet printing technology is used to print a binder, or glue, onto a powder bed. The glue sticks the powder particles together to form a 3D structure. This basic technique has been developed for different applications dependent on the type of powder and binder combination. The most successful approaches use low-cost, starch- and plaster-based powders with inexpensive glues, as commercialized by ZCorp, USA, which is now part of 3D Systems. Ceramic powders and appropriate binders as similarly used in the Direct Shell Production Casting (DSPC) process used by Soligen as part of a service to create shells for casting of metal parts.

Molten Material Systems

Molten material systems are characterized by a pre-heating chamber that raises the material temperature to melting point so that it can flow through a delivery system. The most well-known method for doing this is the Fused Deposition Modeling (FDM) material extrusion technology developed by the US company Stratasys. This approach extrudes the material through a nozzle in a controlled manner. Two extrusion heads are often used so that support structures can be fabricated from a different material to facilitate part cleanup and removal.

A single jet piezoelectric deposition head lays down wax material. Another head lays down a second wax material with a lower melting temperature that is used for support structures. The droplets from these print heads are very small so the resulting parts are fine in detail. To further maintain the part precision, a planar cutting process is used to level each layer once the printing has been completed. Supports are removed by inserting the complete part into a temperature-controlled bath that melts the support material away, leaving the part material intact. The use of wax along with the precision of Solidscape machines makes this approach ideal for precision casting applications like jewelry, medical devices, and dental castings. Few machines are sold outside of these niche areas.

The 1D channel approach, however, is very slow in comparison with other methods and applying a parallel element does significantly improve throughput. The Thermojet technology from 3D Systems also deposits a wax material through droplet-based printing heads. The use of parallel print heads as an array of 1D channels effectively multiplies the deposition rate. The Thermojet approach, however, is not widely used because wax materials are difficult and fragile when handled. Thermojet machines are no longer being made, although existing machines are commonly used for investment casting patterns.

Solid Sheet Systems

One of the earliest AM technologies was the Laminated Object Manufacturing (LOM) system from Helisys, USA. This technology used a laser to cut out profiles from sheet paper, supplied from a continuous roll, which formed the layers of the final part. Layers were bonded together using a heat-activated resin that was coated on one surface of the paper. Once all the layers were bonded together the result was very much like a wooden block. A hatch pattern cut into the excess material allowed the user to separate away waste material and reveal the part.
A similar approach was used by the Japanese company Kira, in their Solid Center machine, and by the Israeli company Solidimension with their Solido machine. The major difference is that both these machines cut out the part profile using a blade similar to those found in vinyl sign-making machines, driven using a 2D plotter drive. The Kira machine used a heat-activated adhesive applied using laser printing technology to bond the paper layers together. Both the Solido and Kira machines have been discontinued for reasons like poor reliability material wastage and the need for excessive amounts of manual post-processing. Recently, however, Mcor Technologies have produced a modern version of this technology, using low-cost color printing to make it possible to laminate color parts in a single process.

Post processing of AM parts

What is post-processing?

Post-processing is an essential stage of additive manufacturing. It's the last step in the manufacturing process, where parts receive finishing touches such as smoothing and painting.

Why is post-processing important?

Post-processing improves the quality of parts and ensures that they meet their design specifications. The finishing process can enhance a part's surface characteristics, geometric accuracy, aesthetics, mechanical properties, and more. For samples and prototypes, this can mean the difference between a sale or a loss. For production parts, finishing creates a part that is ready to use.

A metal additive manufacturing (AM) part is essentially "welded" to the build plate, and you will not be able to pull it off without some assistance. Even then, the AM part will need postprocessing before it is ready to use. Here are some costs associated with postprocessing AM parts.
Powder Removal: AM parts build "down" in a powder-bed fusion system as new layers are added to the top, which means that parts are buried in powder when they are done (see Figure 1). After the build has finished and the parts/build plate have cooled, the machine operator has to remove all of the powder from the build volume and sieve/filter/recycle it for later use, assuming you want to reuse it. This is not an expensive step, but it does take time.

Stress Relief: The heating and cooling of the metal as the part builds layer-by-layer leads to internal stresses that must be relieved before the part is removed from the build plate. Otherwise, the part may warp or even crack. Stress-relieving the part requires an oven or furnace (preferably with environmental controls) that is big enough to fit the entire build plate. Many recommend using an oven with an inert environment to minimize oxidation on the part surface. Others prefer a vacuum furnace, which costs a lot more ($100,000 versus $10,000 to $30,000). Stress-relieving a batch of parts typically costs $500 to $600, plus shipping.

Part Removal: Most companies use wire EDM to remove parts from the build plate, however many machine shops are starting to use a bandsaw (see Figure 2) because it is faster and the bottoms of the parts must be finished anyway. Keep in mind that materials such as Inconel strain-harden as they are worked, making it difficult to remove them from the build plate with just a bandsaw. Using a local machine shop, we spend about $200 to $300 per plate for wire EDM, which can take a few hours depending on the number and size of the parts. A bandsaw can complete the task in minutes.

Heat Treatment: Heat treatment (aging, solution annealing and so on) improves the microstructure and mechanical properties of the parts and is necessary for nearly all AM parts. In many cases, this step also requires an environmentally controlled furnace with the ability to regulate the temperature and cool-down schedule. Heat treatment may affect the dimensions of the parts, so most people prefer to heat-treat parts before they machine/finish them. The American Society for Testing and Materials (ASTM) just released a standard for thermal postprocessing of metal AM parts. Heat treatment can easily cost $500 to $2,000 depending the material and how many parts are being treated.

Hot Isostatic Pressing: Instead of heat treatment, many aerospace companies are starting to use hot isostatic pressing (HIP), which is frequently used in the casting industry to improve the fatigue life of cast parts. A HIP system costs substantially more than a furnace/oven and comes with its own safety measures due to the high pressures (100 megapascals or more) at which it operates. Like heat treatment, HIP costs $500 to $2,000, but you often do not need to heat treat the part if you HIP it.

Machining: Machining of mating interfaces, surfaces, threads, support structures and more likely will be required to ensure dimensional accuracy of the finished part (see Figure 3). Few AM parts meet specifications "as built," and if nothing else, the surface of the part that was connected to the build plate will need to be finished. Most manufacturing companies already have machining systems on hand, but registering parts and establishing datums for machining can be tricky, especially for complex, organically shaped parts made with AM. Accessing internal channels or cooling passages that need to be machined can also increase costs. The cost here is highly dependent on the material and the job as well as the fixturing needed to hold the part.

Surface Treatments: Surface finishing also might be required to improve surface finish/quality, reduce surface roughness, clean internal channels or remove partially melted particles on a part. When outsourced, these costs can easily run in the hundreds if not thousands of dollars.

Inspection and Testing: Metrology, inspection and nondestructive testing using white/blue-light scanning, dye-penetrant testing, ultrasonic testing, computed tomography (CT) scanning and more will be needed after post processing and possibly at multiple points during post processing. Destructive testing of sample parts and analysis of witness coupons (for example, tensile bars), powder chemistry, material microstructure and more also may be needed to gather data to help with process qualification and ultimately part certification. Most companies will have a range of metrology and non-destructive testing methods on hand, but AM parts with internal channels, lattice structures and other internal enhancements may require CT scanning to ensure clear passageways, evaluation of internal geometries and more. A CT scanner will easily cost $1 million to buy, install and operate.

Guidelines for process selection

A variety of AM technologies have been developed. According to ASTM Standard F2792 (ASTM F2792-12a 2012), these technologies can be catalogued into seven groups: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photo-polymerization. More than 350 industrial AM machines and 450 materials have been identified in the market (Senvol LLC 2015). The debate about which machine or technology fares better than others has little value as each of them has its targeted applications. AM technologies are no longer limited to prototyping usage, but are increasingly also being used for making end products (Rosen 2007). Therefore, 'Design for Additive Manufacture' (DfAM) becomes increasingly significant for avoiding potential manufacturing pitfalls and maximizing utilization of AM capability (Rosen 2007, Adam, Zimmer 2014). To achieve that, the designer needs to be able to select a proper AM process in the early design stage. Therefore, a comprehensive and robust selection system becomes paramount for users to select a machine/technology that is fit for purpose (Moylan et al. 2012).

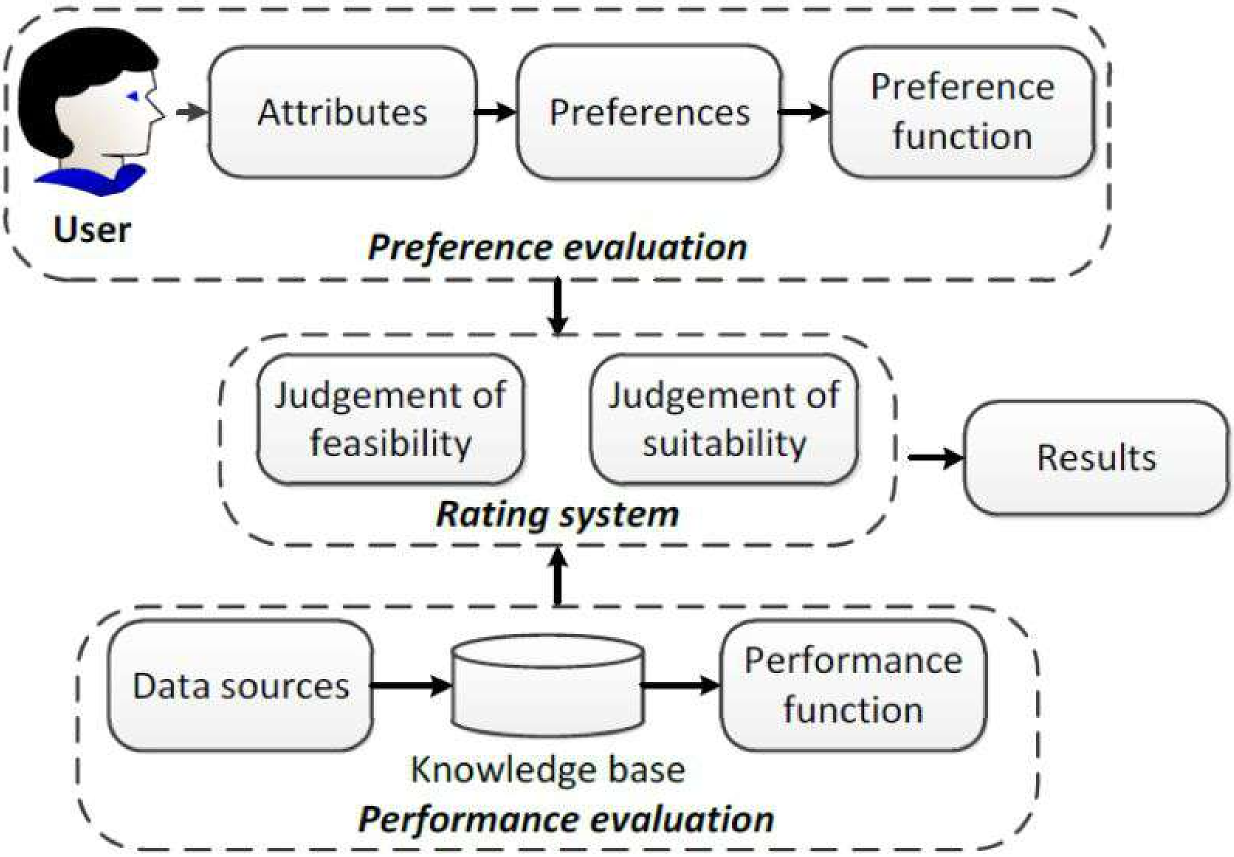
Unlike conventional manufacturing process selection, AM process selection is still a nontrivial task. For each of the various conventional manufacturing processes, a wealth of knowledge has been accumulated over the years. Much of it has become engineering "common sense", and different systems have evolved over the years to suit their preferred and perceived applications. The same however cannot be said about AM processes. AM processes are free from many conventional manufacturing constraints in that they can produce nearly any geometric feature with little auxiliary tools. While the different AM processes show considerable overlap in terms of possible applications, there are also significant differences between the various AM technologies and processes in terms of suitable materials and quality of printed parts. Because it is a relatively new technology, most users do not have enough knowledge and experience to make good judgments. Various knowledge based decision support systems (kb-DSS) to help users make sensible decisions have been published. This paper reviews a number of these kb-DSS solutions for AM process selection and examines their ability to guide the user in a DfAM approach which aims at maximising the benefits derived from AM. We propose a framework that uses concepts from decision theory and the notion of performance and preference functions.

Decision support systems can generally be described by the normative decision theory, which addresses the problem of how decisions should be made in order to maximise the value of outcomes for the user. In order to do that, the theory assumes a *fully informed* and *rational* user who is able to *compute exactly*. Obviously, a kb-DSS is particularly suited to improve the level of information available to the user (stored in the knowledge base) and the ability to compute exactly.

The commonly used decision process can be described by a six-stage sequential decision-making model as proposed

• Identification of the problem
• Obtaining necessary information
• Production of possible solutions
• Evaluation of such solutions
• Selection of a strategy for performance
• Implementation and subsequent learning and reformulation

Inclusion of a kb-DSS alters this process considerably, in particular stages 2 and 3. Without a kb-DSS, in stage 2 the user would obtain information about potential solutions and then assemble that information into possible solutions (stage 3). In contrast, the kb-DSS holds this information about possible solutions within its knowledge base and requests the user's problem description as 'necessary information' in stage 2. A common characteristic for both alternatives is the need of a complete understanding of the problem by the user as a starting point. The 'problem' in this case can be described as a set of user preferences, through which all relevant attributes (such as dimensional accuracy and surface finish) as well as their desired/preferred target values are identified and ranked against each other.



Typical procedure of AM process selection

Figure summarizes the typical procedure of selecting an AM process according to our framework. There are two predominant issues – preference evaluation and performance evaluation. The outcomes of two modules can be combined and generate the ratings for different alternatives.

Firstly, the user's problem description can be captured by using the notion of a preference function. A rational user's preferences can be translated into preference function $Pr_i(x)$ for the ith attribute and can be combined into an overall preference function $Pr^{overall}(x)$, where i indicates the ith attribute ($0 < i \leq n$) and x indicates the value of an attribute.

Similarly, performance functions $P_{i,j}(x)$ can be built, where j indicates the jth alternative ($0 < j \leq m$), describing a 3D printer's performance with respect to the ith attribute.

Preference evaluation

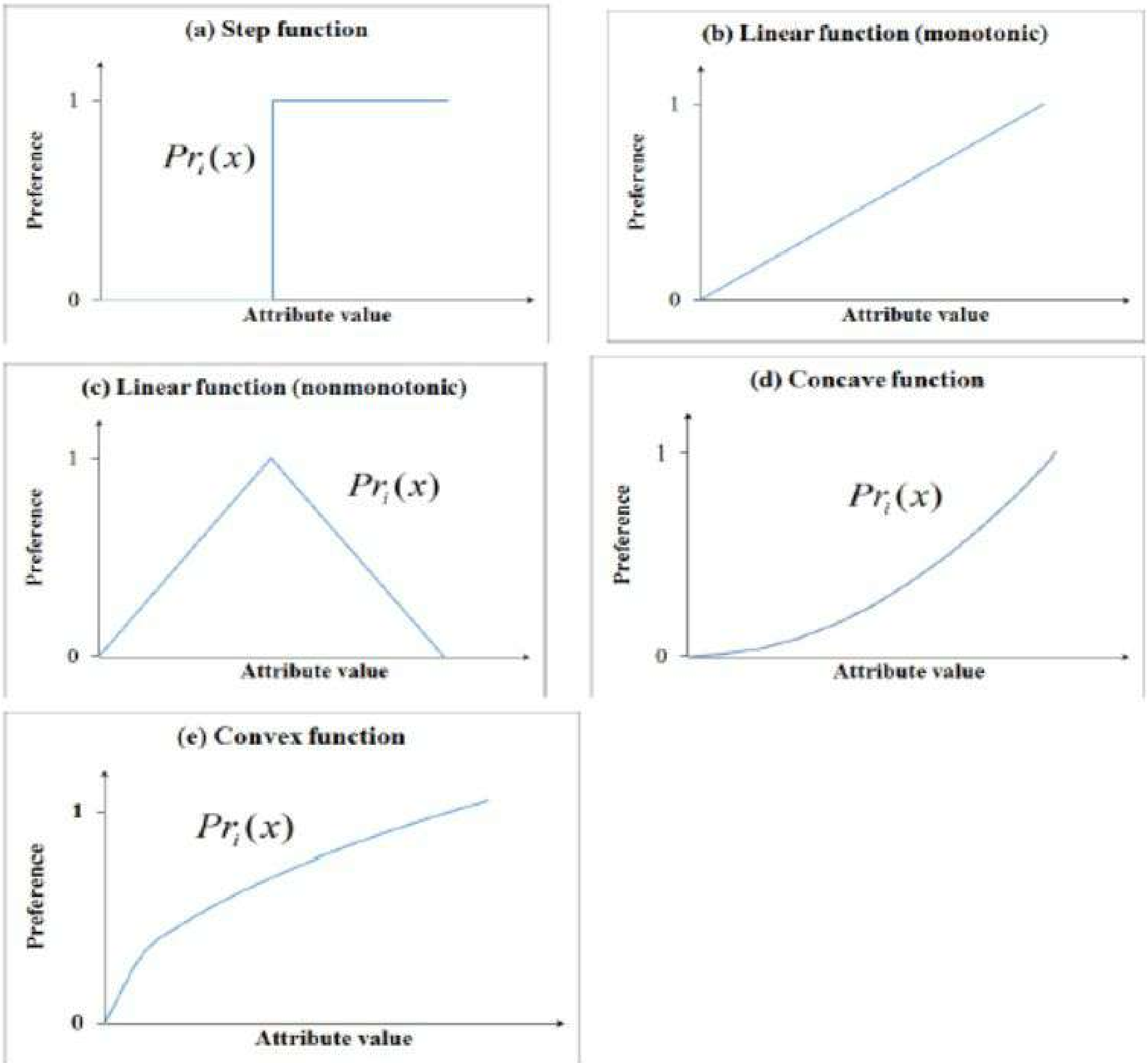
As described in the previous section, the merit of a kb-DSS largely depends on the question whether the users are rational with respect to their preferences. A rational user's preferences have to fulfil two essential requirements: completeness and transitivity (Hansson 2005). In practical terms, completeness means the user has to be able to articulate a preference for *every possible* attribute value compared to *all other* attribute values. Formally, this means: *for any elements* A *and* B *of its domain, either* $A \geq B$ *or* $B \geq A$ *has to hold.* While the user in most cases will be able to articulate these preferences, the main challenge will be for the kb-DSS to capture all of that information so that the completeness still holds. The transitivity requirement means that *for all elements* A, B *and* C *of its domain, if* $A > B$ *and* $B > C$, *then* $A > C$. While this sounds completely logical in theory, practical examples often show that preferences articulated by the user do in fact not satisfy the criteria

Implicitly or explicitly, all the **methods for selecting AM processes** formulate various preference functions to describe users' preferences. Usually more than one attributes need to be considered. To exactly describe users' preferences, a plurality of information is needed from users, e.g. the thresholds (lowest and/or highest levels) they accept for each attribute, the shape (monotonicity and curvature) of the preference curve for each attribute, the interdependency of the attributes and the trade-offs between all attributes. The monotonicity of preference indicates whether the preference is consistently increasing/decreasing (monotonic) or increasing/decreasing towards a goal (non-monotonic).

Depending on the level of the detail to which the user's preferences have been captured, we divide **AM process selection methods into two groups:** *Judgement of Feasibility* (JoF) and *Judgement of Suitability* (JoS). The JoF approach only considers the lowest acceptable level for each attribute and uses that to decide whether a given solution can fulfil users' requirements. In contrast, the JoS approach mainly considers the trade-offs between different attributes and recommends the best marked solution for users while the threshold is usually not taken into account.

JoF approach

The Judgement of Feasibility approach is utilized to rule out unfeasible solutions, i.e. solutions with a performance below the threshold. This approach defines two indifference levels. Any performance above the threshold is equally preferable for users, i.e. the preference function for each attribute takes the form of a step function as shown in Figure


(a) Step function
Preference
Attribute value
$Pr_i(x)$
1
0
(b) Linear function (monotonic)
Preference
Attribute value
1
0
(c) Linear function (nonmonotonic)
Preference
Attribute value
$Pr_i(x)$
1
0
(d) Concave function
Preference
Attribute value
$Pr_i(x)$
1
0
(e) Convex function
Preference
Attribute value
$Pr_i(x)$
1
0

$$Pr_i(x) = \begin{cases} 0 & x < \theta \\ 1 & x \geq \theta \end{cases} \quad (2)$$

where θ is the threshold value, characterizing the user's requirement and x is the performance value for the corresponding attribute.

The overall preference function can then simply be expressed as the sum of individual attribute preference functions:

$$Pr^{overall}(\boldsymbol{x}) = \sum_{i=1}^{n} Pr_i(x_i)$$

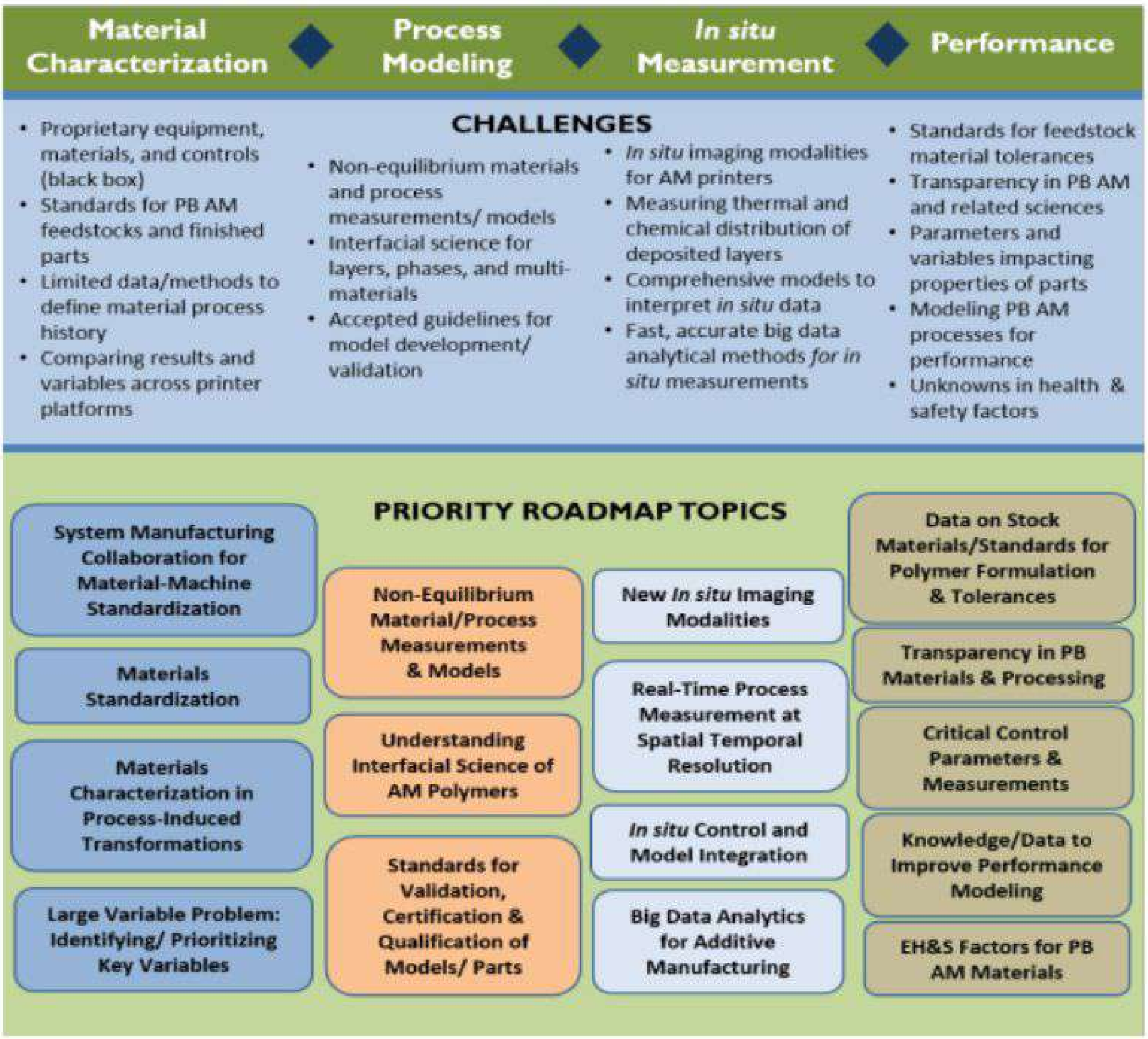
(3)

This is an efficient approach to narrow down the option space. Some attributes are particularly suitable for this kind of function, e.g. build envelope and minimum feature size. However, when all of the user's preferences are simplified into step functions, the approach becomes too rigid and does not allow for trade-offs between attributes. In terms of a DfAM approach that intends to help the user modify the design towards benefiting from the use of AM, the JoF approach therefore has limited value.

JoS approach

For the Judgement of Suitability approach, the preference function can have an arbitrary shape. It is important to note that preference functions are not unique. Instead, different preference functions can be extracted from the same preference structure. $Pr_1^{overall}(x)$ and $Pr_2^{overall}(x)$ are strategically equivalent if $Pr_1^{overall}(x)$ and $Pr_2^{overall}(x)$ have the same indifference curves and induced preferential ordering (Keeney, Raiffa 1976). If there is just one attribute, then the curvature of $Pr^{overall}(x) = Pr_1(x)$ is not important because the indifference curve will not change as long as $Pr^{overall}(x)$ shows a certain monotony. When considering multiple attributes, however, the curvature of $\mathrm{Pr}_i(x)$ does matter since it may influence the monotony of $Pr^{overall}(x) = f(Pr_1(x), Pr_2(x), ..., Pr_i(x))$, which causes the different indifference curves.

Figure E-2. Key Priority Topics and Challenges for Polymer-Based Additive Manufacturing



AM Applications

INDUSTRIES	CURRENT APPLICATIONS	POTENTIAL FUTURE APPLICATIONS
COMMERCIAL AER0SPACE 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

1. Rapid Prototyping
    - Models and parts for research purposes can be easily manufacture whenever required. Easy to make changes in the models as per the research proceedings.
2. Food
    - Cornell Creative Machines Lab is making food items such as chocolates, candy, pasta, pizza using 3D printing technique since 2012.
3. Apparel
    - Products such as customize shoes, clothes and eye wears are being manufactured.
    - Nike is using 3D printing to manufacture the "Vapor Laser Talon" football shoe for players of American football
4. Vehicle
    - In 2010 Urbee became the first car whose whole body was 3D printed (by US engineering group Kor Ecologic and the company Stratasys).

- In early 2014, Swedish supercar manufacturer, Koenigsegg, manufactured a supercar having many 3D printed mechanical parts in it.

5. Firearms
   - Defense arms such as guns, rifles and safety equipment has also been manufacture byAM.
   - In 2012 US based group "Defense Distributed", designed a working plastic gun that could be downloaded and reproduced by anybody with a 3D printer.
   - In 2013, 'Solid Concepts', based in Austin, Texas, USA succeeded in manufacturing first working metal gun.
6. Medical
   - Nowadays medical devices, specific implants, hearing aids, dental products and pills are being manufacture byAM.
   - During October 2014, a five year old girl born without fully formed fingers on her left hand became the first child in the UK to have a prosthetic hand made with 3D printing . Till now more than 400 hands have been transplanted by E-NABLE.
   - In august 2015, US FDA(Food and Drug administration) approved 3D printed pills which allows very porous pills to be produced, which enables high drug doses in a single pill which dissolves quickly and can be ingested easily.
7. Bioprinting
   - Bioprinting refers to manufacturing artificial biological organs and body parts capable of working like original ones.
   - In this process, layers of living cells are deposited onto a gel medium or sugar matrix and slowly built up to form three dimensional structures including vascular systems.
   - The first production system for 3D tissue printing was delivered in 2009, based on NovoGen bio-printing technology.
   - In 2013, Chinese scientists began printing ears, livers and kidneys, with living tissue.
   - In 2014, researchers at the University of Hasselt, in Belgium had successfully printed a new jawbone for an 83 year old woman.
8. Space
   - In September 2014, "SpaceX" delivered the first zero gravity 3D printer to the International Space Station (ISS).
   - In December 2014, NASA emailed CAD drawings for a socket wrench to astronauts aboard the ISS, who then printed the tool using its 3D printer.
   - The European Space Agency plans to deliver its new advance Portable OnBoard 3D Printer to the International Space Station by the end of 2015.