Additive Manufacturing

Turning Mind into Matter

Industry Evaluation and Recommendations Report

SIERRA COLLEGE

CACT

Centers for Applied Competitive Technologies

MAKING IT IN CALIFORNIA

Prepared for

Sierra College Center for Applied Competitive Technologies (CACT)

By

Neal de Beer (PhD)

May 31, 2013

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Focus of This Report

The purpose and aim of this report is to provide insight into the growing field of Additive Manufacturing (AM) for the Center of Applied Competitive Technologies (CACT) at Sierra College in Rocklin, CA. The report aims to identify industry sector groups and potential applications for the expansion or improvement of existing services that the CACT currently offers in the area of AM. Technology resources needed are also identified and recommendations are made on how to transfer new technology skills to instructional programs and industry partners. An important aspect of this lies in building awareness and cross-sector collaboration around the use of 3D printing technologies. Further recommendations are also made in this regard.

The Additive Manufacturing (AM) industry has undergone tremendous growth in recent years since its 26-year history started back in 1987 with the first commercialization of stereolithography [1]. With a steady incline in the number of annual US patents (910 applications, 539 issued in 2012), the AM industry is still showing signs of new technological innovation [2]. Further proof of this is seen in the explosion of new 3D Printer companies and their products (see a list of these companies in Appendix B), several in the low-cost market, which is creating opportunities for adoption of this technology by the masses in a way that has never been economically feasible in the past.

The ASTM International Committee F42 on Additive Manufacturing Technologies (formed in 2009) has defined additive manufacturing as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.

In this fast-growing, ever-changing industry, terminology evolves rapidly. The mainstream press, the investment community, and the CAD industry – three influential groups, make use of the term "3D printing" when referring to AM technology and the industry it represents. So although Additive Manufacturing may be the official industry standard term, 3D printing has become the de facto industry standard. Consequently, this report uses the terms Additive Manufacturing and 3D printing interchangeably.

The report is structured in two main parts. Part 1 describes the background and current trends of AM, covering a brief historical account of the past year; discussions on new applications for different industry groups; and ending off with a discussion on the emerging DIY maker community and a host of new business models that are challenging conventional ways of product development and distribution.

Given the background of new developments described in Part 1, the second part of this report looks at how CACT can align its future strategies to the rapidly changing AM industry, keeping in mind its current goals and constraints. These recommendations are framed along three sequential partnership groups that are facilitated by the CACT, namely high schools (for early exposure), college students and faculty departments (to build skilled labor), and industry partners (to serve needs for *making it in California*).

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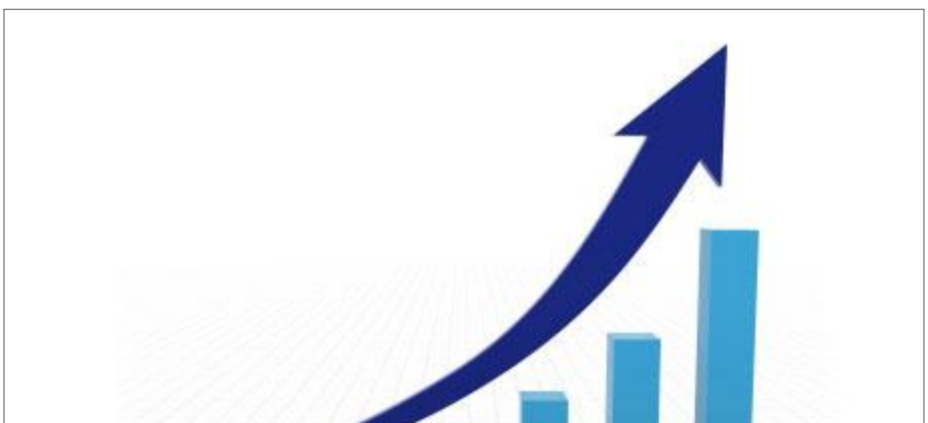
Glossary of Abbreviations

ABS	Acrylonitrile butadiene styrene material
AM	Additive Manufacturing
AMF	Additive Manufacturing File
ASTM	American Standards and Testing Methods
CACT	Centers of Applied Competitive Technologies
CAD	Computer Aided Design
CT	Computed Tomography
DoD	Drop-on-Demand
DOD	Department of Defense
DOE	Department of Energy
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
ISO	International Organization for Standardization
MIT	Massachusetts Institute of Technology
MRI	Magnetic Resonance Imaging
NAMII	National Additive Manufacturing Innovation Institute
NCDMM	National Center for Defense Manufacturing and Machining
NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
PLA	Polylactic Acid. Material that is used for creating support structures during 3D printing
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Standard Triangular Language file format

Background & Current Trends



Part 1

Part 1 – Background and Current Trends

1 Recent History of Additive Manufacturing

The Additive Manufacturing (AM) industry has been vibrantly active with several new startups entering the market as well as some major acquisitions and mergers that occurred, notably the acquisition of the 3D printer manufacturer Z Corp. (Burlington, Massachusetts) by 3D Systems and the merger between Objet and Stratasys. This section will focus mostly on the recent history of developments in the industry and much of it has been adapted from the 2012 Wohlers Report [1]. A more comprehensive list of events, beginning with the initial commercialization of stereolithography in 1987 up until May 2011, is available to download as a 26-page document from the website of Wohlers Associates [3].

In 2012, the AM technology skyrocketed into the public eye through many articles in major publications, television programs, and even a few movies. Materialise hosted a fashion show that featured AM-produced hats and accessories at its World Conference in April 2012.

Low-cost machines in the sub-$2,000 range are being purchased in record numbers for academic and personal use. According to Wohlers, this activity however has had little impact on overall industry revenues [1]. But printer manufacturers have recognized this growing trend and the need to make 3D imagery and content more easily accessible to the personal 3D printer market.

In July 2011, Stratasys announced a new crossover AM machine, the Fortus 250mc, which runs the ABSplus material with a soluble support material. A new static dissipative material, ABS-ESD7, was released for use on the Fortus 400mc and 900mc platforms. Also in July 2011, the ASTM International Committee F42 on Additive Manufacturing Technologies released the specification for its Additive Manufacturing File (AMF) format. The new format supports textures, functionally graded material information, color, curved triangles (for better quality meshing), and other elements not supported by the STL file format. Despite its advantages over the commonly-used STL format, the adoption and use of this new AMF file format has been slow, with most people still making use of the STL format that they are familiar with. Read more about the benefits of the AMF format in Section 2.2.

In September 2011, Buildatron Systems (New York, New York) announced the availability of its RepRap-based Buildatron 1 3D printer. In the same month, 3D Systems released the ProJet 1500, a machine based on film transfer imaging, as well as the Bits from Bytes 3DTouch product. Solidoodle (Brooklyn, New York) introduced its RepRap-based Solidoodle 3D printer. The founder of Solidoodle is none other than the previous COO of MakerBot, Sam Cervantes.

In October, ASTM International and the International Organization for Standardization (ISO) announced a cooperative agreement between ASTM International Committee F42 and ISO Technical Committee 261 on Additive Manufacturing. The agreement will reduce a duplication of effort. ASTM F42 released a standard terminology for coordinate systems and test methodologies.

In November 2011, 3D Systems announced that it would acquire long-standing 3D printer manufacturer Z Corporation (Burlington, Massachusetts). In the same month, Stratasys extended its WaterWorks soluble support material to work with its polycarbonate build material. In terms of online content development, Tinkercad (Finland) raised $1 million in seed funding to continue development of its web-based design software and printing service. The 3D content and on-demand services company Shapeways, based in New York, announced its plans to open a manufacturing facility just outside of New York. Shapeways has made a really big impact on the 3D printing industry by streamlining their processes and business model to allow user-friendly online access to upload personal 3D content and have it produced at competitive pricing and variety of materials. Further to this, users can then post their designs for sale on Shapeways' website and share in the profit when someone else orders a product made from their design. Several other companies are following suit, which will be discussed later in this report. Shapeways however has attracted the attention of investors Chris Dixon and Andreessen Horowitz, who in April 2013 announced that they are making a $30 million investment in Shapeways. [4]

"3D printing is important because so much of what we've done over the last 20 years has been moving bits around. Now we're starting to see tech impact the physical world," said Dixon, who is joining the Shapeways board of directors.

Geoffrey Doyle, CEO of GrowShapes (Mountain View, CA), commented on LinkedIn that "Interestingly, this VC investment capital so far in 2013 is now more than all investments made during 2012!"

In January 2012, MakerBot (Brooklyn, New York) released the MakerBot Replicator, with a larger build volume than its predecessor. A second extruder head option is available to run multiple colors of ABS or PLA support material. 3D Systems announced a sub-$1,300, single-material, consumer-oriented 3D printer called the Cube. The machine has wireless connectivity, and 3D models that can be downloaded from 3D Systems' digital design library.

February 2012 saw 3D Systems' release of Print3D, a plug-in for CAD programs such as Solidworks and Pro/Engineer. It gives dynamic part costing for parts and assemblies through 3D Systems' ProParts service organization.

In April 2012, Stratasys and Objet announced their intention to merge, and on December 3rd, 2012, the merger was completed with the combined company now called Stratasys, Ltd. with dual headquarters in Eden Prairie, Minnesota and Rehovot, Israel. David Reis, CEO of Objet, remained CEO of the merged company, while Scott Crump, CEO of Stratasys, now serves as chairman. Also in April, only a few months after introducing their first 3D printer, Solidoodle announced its second-generation machine for $499.

Stratasys introduced its new Mojo 3d printer in May 2012. The system engineered from the ground up, combines the extrusion head and material into a single consumable print engine. The new design has apparently eliminated the need to replace tips and heads.

In June 2012, Stratasys announced a joint initiative with the U.S. Department of Energy (DOE) at Oak Ridge National Laboratory (ORNL) to jointly develop fused deposition modeling (FDM) additive manufacturing to foster energy efficient production. The project targets two main objectives: First, the development of in-process inspection to assure part quality and suitability for service; and secondly, the development of carbon fiber reinforced FDM feedstock materials to produce strong, lightweight components.

Also in June 2012, Objet announced that it is breaking the 100 material range barrier by making 39 new 'Digital Materials' available with its Objet Connex range of multi-material 3D printing systems. 'Digital Materials' are derived by the composite mixing of two primary Objet materials. The two materials are combined in specific concentrations and structures, to provide the desired mechanical properties and to resemble the product's target materials. Users can now select from 107 materials ranging from opaque or transparent rigid to rubber-like substances, and combine up to 14 different materials in the same model – a unique ability for the AM industry.

Figure 1 – Variety of Objet materials produced in one build using AM

In July 2012, Solidscape, a manufacturer of high precision 3D printers, a Stratasys company, announced the launch of the 3ZPRO high precision wax 3D printer. The Solidscape printers combine patent-protected, drop-on-demand ("DoD") thermoplastic ink-jetting technology and high-precision milling of each layer to build a part, thereby creating parts with very high quality and surface finish for investment casting.

August 2012 saw a number of exciting developments in the AM industry. On August 16th, White House officials announced a $30 million investment to create a National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio aiming at boosting 3D printing technology. Driven by the National Center for Defense Manufacturing and Machining (NCDMM), under the leadership of Ralph Resnick, NAMII serves as a nationally recognized additive manufacturing center of innovation excellence, working to transform the U.S. manufacturing sector and yield significant advancements throughout industry.

Also in August 2012, the technology research and advisory company, Gartner Inc., released their 2012 Hype Cycle for emerging technologies. Their graph reveals, according to their estimation, that 3D printing is about to reach its peak of inflated expectations, and should reach its plateau in 5 to 10 years. Trailing behind on the curve is the 'Internet of Things', 3D Scanners and still in its very early stages of development, 3D Bioprinting.

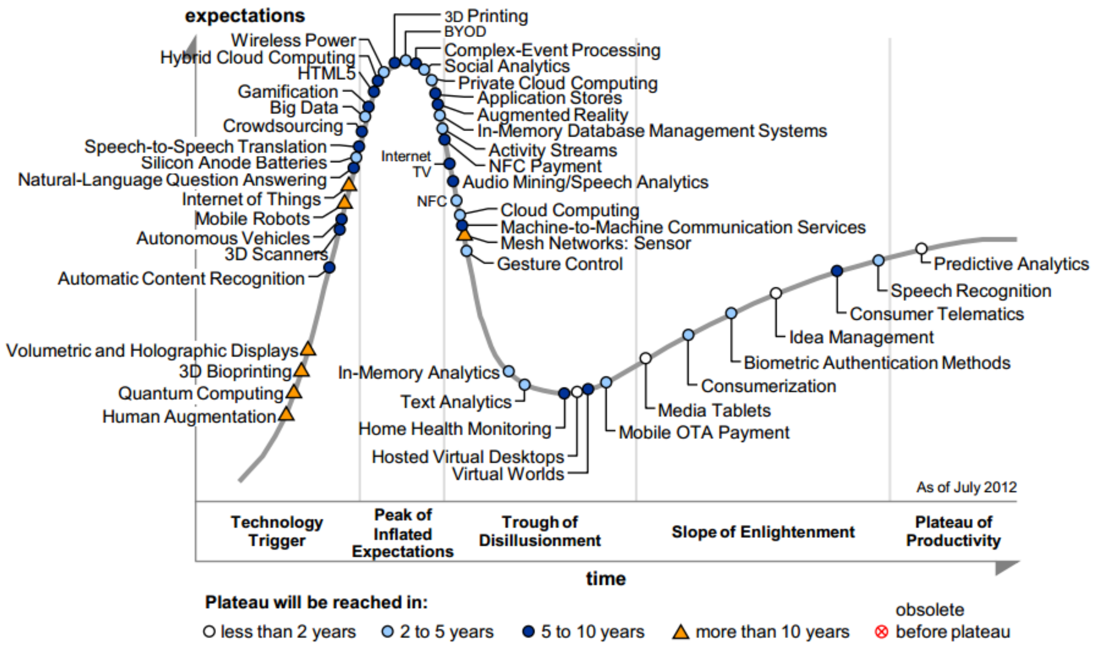


Figure 2 – Gartner, Inc. 2012 Hype Cycle for Emerging Technologies [5]

Another information matrix that was released by Tuan Tranpham, from Objet Inc., helps to compare the various role-players in the AM industry [6]. The horizontal axis, from left to right follows the stages of development from obtaining 3D content to producing the physical part. The vertical axis, from the bottom up shows the different categories of user-groups for each of the various technologies presented.

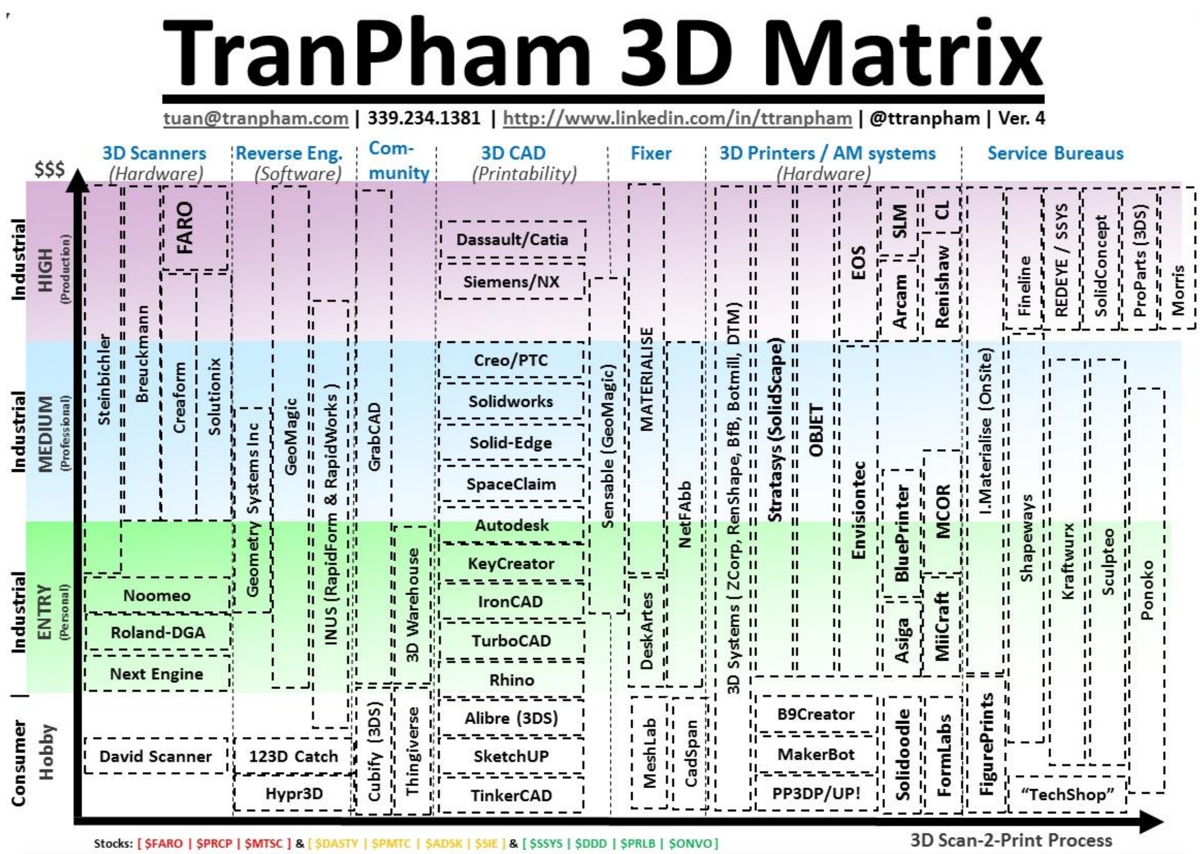


Figure 3 – The TranPham 3D Matrix of industry role players [6]

In September 2012, MakerBot announced the release of its latest 3D printer, the Replicator 2. MakerBot has developed a good reputation in the industry for providing 3D printers to produce relatively high quality parts in ABS (PLA support material), in various colors. They have tried to improve on their previous printer with the Replicator 2 featuring a 100-micron layer thickness, and priced competitively at $2,199.

In October 2012, 3D Systems announced that it acquired Rapidform, a leading global provider of 3D scan-to-CAD and inspection software tools, located in Seoul, South Korea for $35M in cash, subject to final closing adjustments. Shapeways also announced its plans to construct a factory in Long Island City, NY, that is set to becoming the biggest 3D printing manufacturing facility in the world. At 25,000 square feet, the expansive facility will house between 30 to 50 industrial-size 3D printers.

In November 2012, Solidscape Inc. announced the launch of their new 3Z™ LAB 3D wax printer. Ideal for use in the dental industry, the 3Z LAB printer can produce crowns, bridges and copings in wax material ready for dental lab technicians to cast. At Euromold 2012 in Frankfurt, Germany several new announcements were made. Mcor Technologies announced the availability of their IRIS (paper-based) color 3D printer. Mcor also announced an agreement with Staples Printing Systems Division to launch a new 3D printing service named “Staples Easy 3D” – an online service via the Staples Office Center. Objet launched its largest ever 3D printer. The Objet1000 features a 1000 x 800 x 500 mm (39.3 x 31.4 x 19.6 inch) wide-format build envelope, which is suited for automotive, defense and aerospace, industrial machinery, consumer goods and household appliance sectors that need to create industrial size, 1:1 scale prototypes. 3D Systems also launched its next generation ProJet® 3500 HDMax and CPXMax professional series 3D printers.

In December 2012, Stratasys and Objet announced the completion of their merger, with their total market valuation estimated to reach approximately $3 Billion. Organovo, a creator and manufacturer of 3D human tissues for medical research and therapeutic applications in San Diego, CA, announced that it is working together with researchers at Autodesk to create the first 3D design software for bioprinting. No timeline is announced for when the software will be released, however the software, which will be used to control Organovo's NovoGen MMX bioprinter, has the potential to open up bioprinting to a broader group of users.

At the beginning of January 2013, 3D Systems announced that it had signed an agreement to acquire Geomagic, Inc., a provider of 3D authoring solutions including design, sculpt and scan software tools that are used to create 3D content and inspect products throughout the entire design and manufacturing process. Geomagic Founder and CEO, Ping Fu, has become the Chief Strategy Officer of 3D Systems. Shortly after this news, 3D Systems also introduced their new Cube and Cube X 3D printers. One day later, Makerbot unveiled its newest desktop personal 3D printer at the Consumer Electronics Show (CES 2013) – the Replicator 2X.

After the beta release of multi-material and multi-color enhancement kit, RepRapPro announced in February 2013, the release of Tricolour Mendel – an open-source RepRap Mendel 3D printer designed to work with three colors or three different plastics at the same time. This new design was derived from RepRapPro Mono Mendel, a successful model from 2012. Its primary design goals were to offer a printer which is easy to expand in functionality, which is low-cost, fast to replicate, to assemble and to commission.

Competing against Solidscape for the dental market, EnvisionTEC unveiled in February, their latest addition to their dental lineup – the 3Dent™ SCP 3D printer, specifically for the manufacture of dental models.

In March 2013, Swedish 3D printer manufacturer, Arcam AB, launched their new Electron Beam Melting (EBM) machine – namely Arcam Q10. This latest printer is designed specifically for industrial production of orthopedic implants. Also in March, Autodesk announced a new partnership with MakerBot to jointly market a combination of 3D design software and 3D printing hardware. This collaboration will enable connecting MakerBot Replicator 2 Desktop 3D Printers with the Autodesk 123D family of apps. There will be a send-to-printer option in Autodesk's software that allows users to send their creation in 123D apps straight to the Replicator 3D printer. And Autodesk will help to sell Makerbot's 3D printers through Autodesk's site 123Dapp.com. Also in March 2013, Stratasys announced the launch of the Objet30 OrthoDesk 3D Printer, its first desktop size 3D printer specially designed for smaller orthodontic labs and clinics.

Finally, at the beginning of May 2013, President Obama followed up on previous comments he made during his State of the Union address (in February), about the launch of additional manufacturing hubs similar to the pilot NAMII in Youngstown, OH. The Obama Administration announced on May 9th, 2013 that it is launching competitions to create three new manufacturing innovation institutes with a Federal commitment of $200 million across five Federal agencies – Defense, Energy, Commerce, NASA, and the National Science Foundation. For more information on these projects and how to apply, see further details at www.manufacturing.gov.

2 Applications for Additive Manufacturing

Applications for parts made by additive manufacturing continue to grow. An industry that was once known for rapid prototyping has extended its reach to a broader, more diversified range of possibilities.

As applications grow, the users of the technology grow as well. Once relegated to high-tech laboratories at Fortune 100 companies, AM now is employed by the smallest organizations – and increasingly even by individuals. At every point along that spectrum are users with new ideas and unique applications. It seems that almost any problem involving three-dimensional objects can be solved faster and better with the use of AM technology.

The prerequisite for using AM was once a CAD model, but now input can be generated by medical scan data, entertainment software, as is the case with computer game avatars, and simple drawing and sketching programs. This frees the average individual from the need to learn complex, technical (and relatively costly) software in order to create 3D content for additive manufacturing. In addition, users can purchase 3D content online from companies like Shapeways or download them for free at other companies like Thingiverse.

Prototyping was among the earliest applications of AM technologies and remains one of the most powerful tools for product development. As material quality, surface finish, and dimensional accuracy have improved, AM models have been increasingly used for functional prototyping and for tooling and metal casting processes.

A survey conducted by Wohlers [1], featuring input from 27 system manufacturers and 71 service providers across the world, indicates which industries are being served and their approximate revenues (as a percentage) that they receive from each. The following chart shows the results.

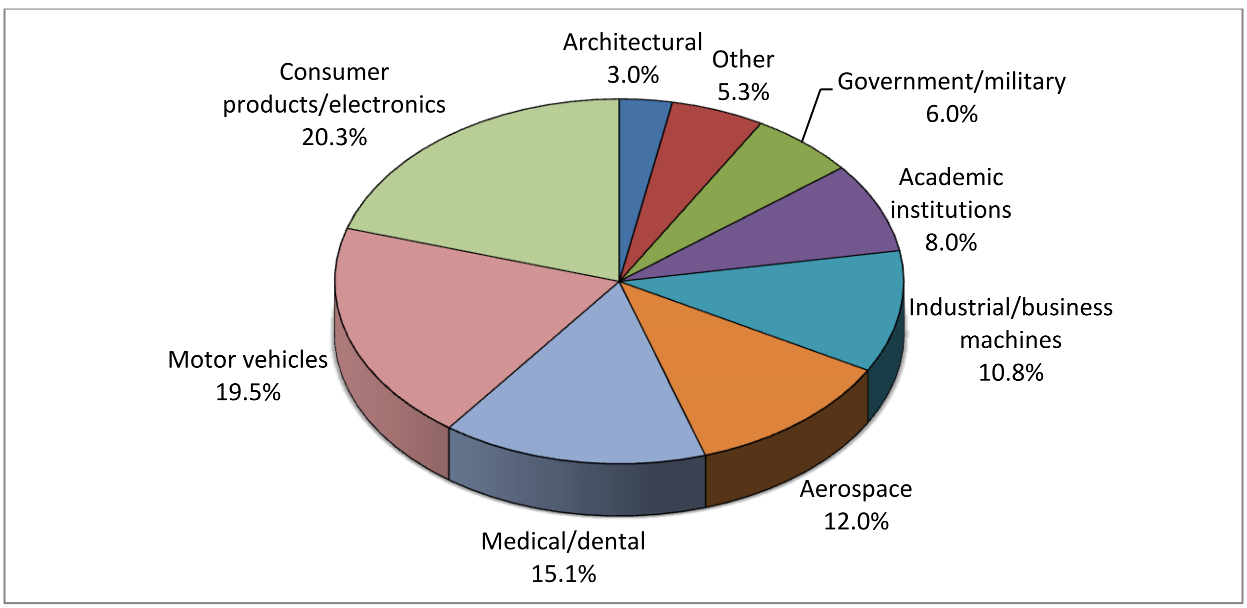


Figure 4 – Industries being served and their revenues by percentage [1]

Consumer products/electronics is the leading industrial sector, as it has been the past seven years, followed closely by motor vehicles. Medical/dental has established itself as a strong sector for AM and has been the third largest over the past 11 years. Aerospace, the next largest, grew from 9.9% in 2011 to 12% in 2012. The “Other” category includes a wide range of industries, such as oil and gas, non-consumer sporting goods, commercial marine products, and various other industries that do not fit into the named categories.

The following chart shows how organizations are using industrial additive manufacturing systems for a range of applications. The survey results show that companies are using AM technology for direct part production and functional modeling more than anything else.

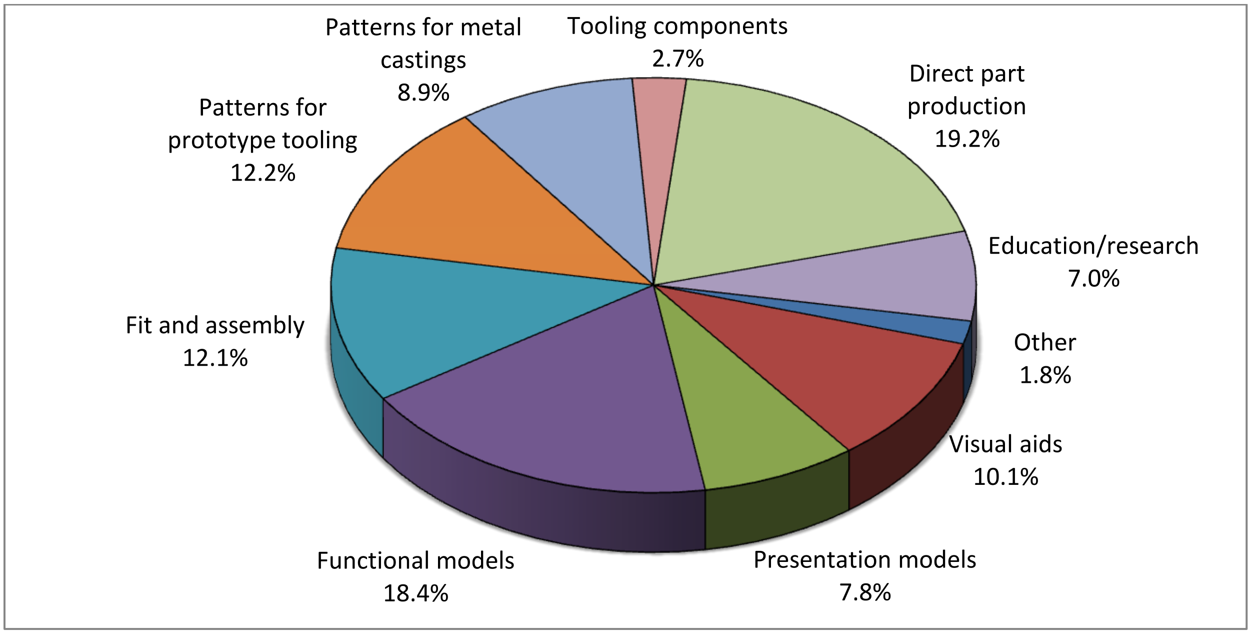


Figure 5 – Range of applications for AM [1]

2.1 Visual Aids and Presentation Models

One of the earliest successful applications for AM has been the creation of models to communicate design intent and offer a first proof of concept. Today, AM continues to be used to create prototype models for visual confirmation of design and to communicate various issues relating to the model being produced. As more and more industries have realized the benefits of using 3D printed models to verify their designs or prepare their planning, the use of this technology for visual aids and presentation models have expanded significantly. Here are a few examples from a list that is by no means complete:

2.1.1 Confirmation of Design and Communication

During the design of new components, designers make use of 3D printed models to confirm various iterations of their design. 3D printing enables the designer to produce multiple iterations of a design in the same amount of time it would take to produce only one model. In addition, a design can be scaled up or down depending on the need required. The ability to visualize the design as a physical 3D model allows the design team to consider various issues from aesthetics to form and function as well as manufacturability, assembly and packaging design. The 3D model also serves as a powerful communication tool between different members of the design team or sub-contractors that may be employed. Furthermore, with a growing variety of materials to choose from, Additive Manufacturing systems can present designers with more than just a visual confirmation. In many cases, designers now have the ability to select a material that more closely resembles their final product's material, and in this way design confirmation can include functional testing of their components. In other cases, secondary processes and finishing may be required to produce a prototype with the appropriate material.

2.1.2 Medical Models

AM has been used extensively to produce surgical or medical models from patient (CT or MRI) scan data, used between surgical teams to perform surgical planning (for both pre- and intraoperative use), preparation or fitment of implants, and communication between surgeons and their patients.

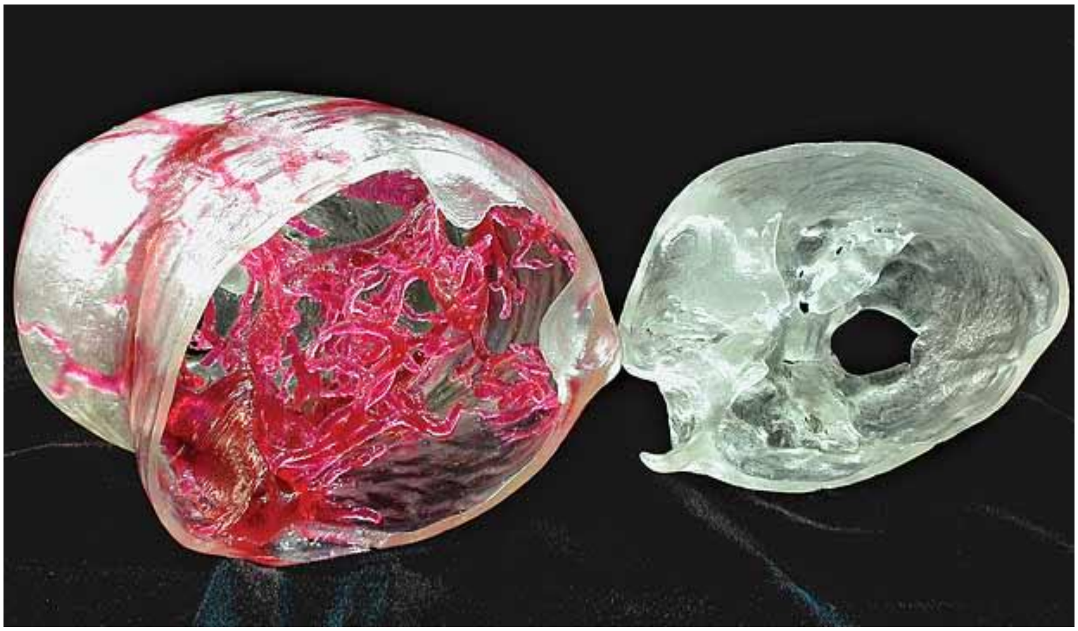


Figure 6 – Medical model of conjoined twins' skull for pre-surgical planning

Figure 7 – Preparing of maxillofacial implant pre-surgically using 3D printed skull

2.1.3 Architectural Models

In the field of architecture, AM is used to produce scaled replica models of buildings and constructions. A continued challenge in this field of application however exists in scaling down features such as window frames and guard railings. When scaling down a construction to a size that can be produced using AM, any such features virtually disappear and need to be reconstructed on the scaled CAD model – which is a time consuming exercise. Below is a selection of examples where 3D printing was used to construct architecture models.

Figure 8 – 3D printed sport stadiums

Figure 9 – Architecture model printed in color

2.1.4 Geological Landscape Models

A related field that makes use of AM models is in the construction of geological landscapes from GIS data and the estimation of mineral or other geological exploits. Here, the value of 3D printing in color is especially valuable to display satellite imaging for landscape models or various color scales for mineral deposits.

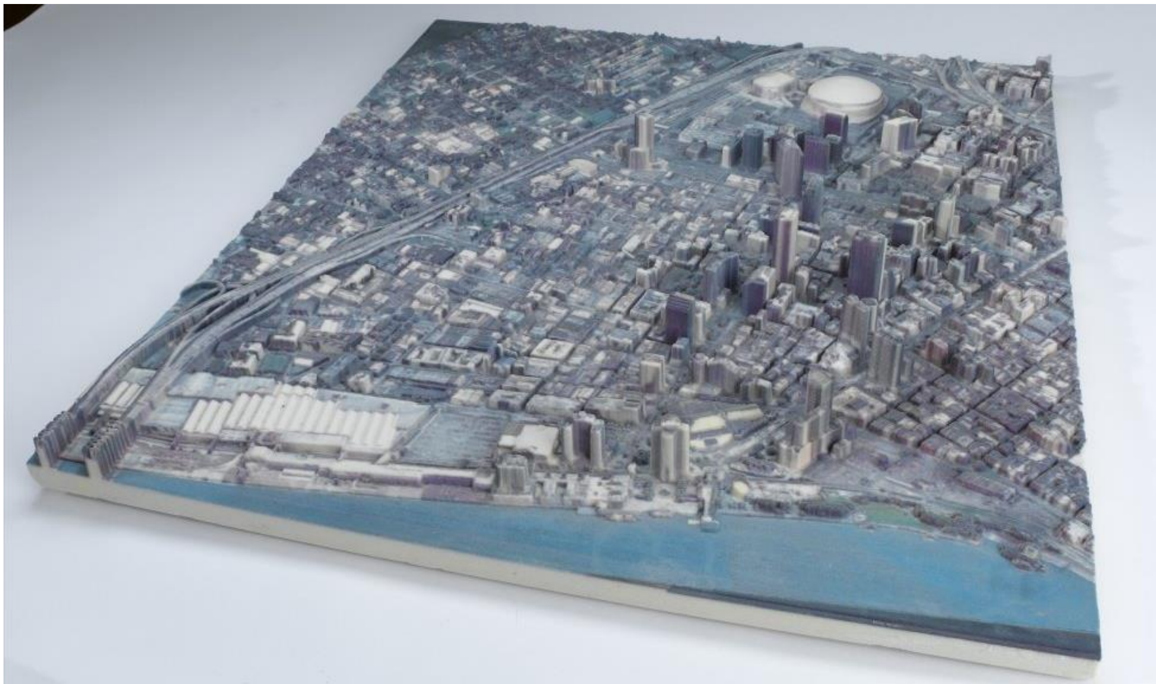


Figure 10 – 3D printed city model from satellite image data

Figure 11 – Geological model created from satellite image data

2.1.5 Design Analysis (FEA) Results

The use of color can play a further significant role in communication of component design or manufacturing. Merely the ability to print black on white enables the designer to print directions or other text on the part for others to consider. Full color models on the other hand, enable the designer to display finite element analysis (FEA) test results in the form of cut-away model sections. Another use for color could be to communicate specific tolerance levels on different faces of a part to machine operators.

Figure 12 – Color 3D printed model indicating FEA test results

2.1.6 Teaching Aid Models

In the field of teaching and education, 3D models are a valuable tool for teachers to bring abstract concepts alive for their learners. The ability to visualize seemingly invisible objects such as the shapes of molecules or cells (scaled up) through 3D printing enables learners to develop a tactile understanding of their learning material.

Figure 13 – Examples of various complex molecule structures that were 3D printed

2.1.7 Market Analysis and Trade Show Exhibitions

In addition to presentation models being used by designers and manufacturers, prototype models of the final design may also be used marketing purposes. As mentioned before, the use of various materials and color printing can yield a model that sufficiently resembles the final product. In some cases however, further post-processing (i.e. surface finishing and polishing, painting or applying other coatings) may be required.

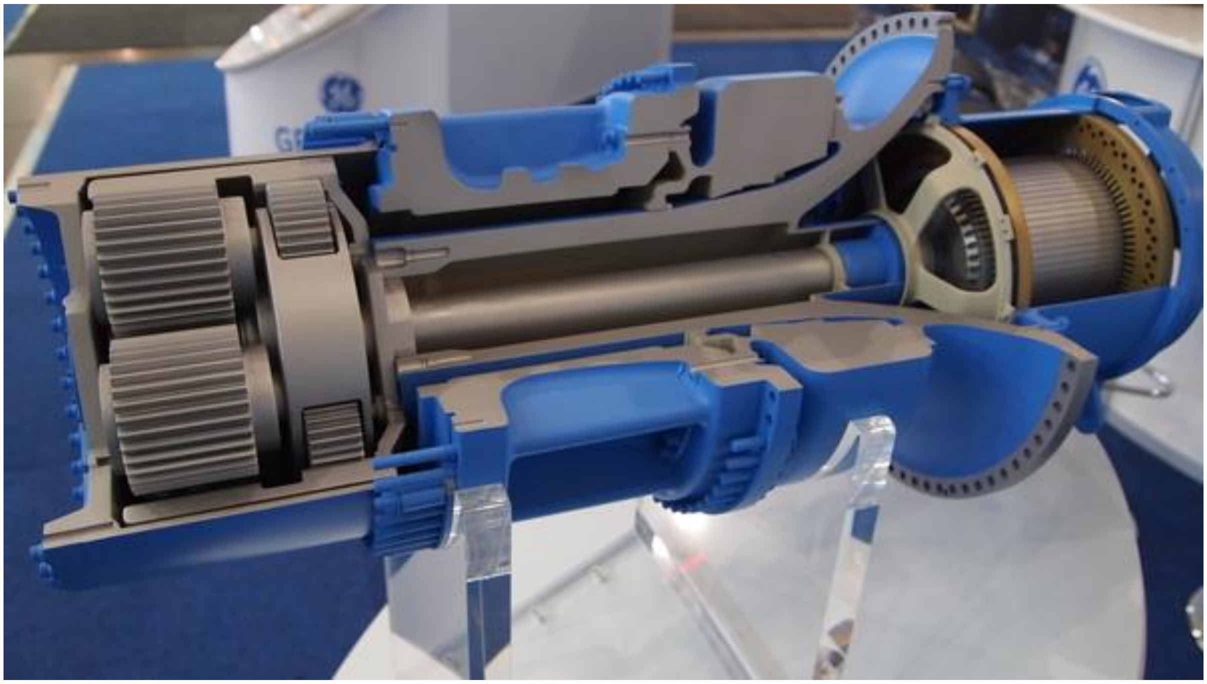


Figure 14 – Scaled down cutaway model of a transmission used at a trade show.

2.2 Direct Part Production

A question that arose early on as Additive Manufacturing grew in popularity, has been whether parts can be manufactured to the various standards (mainly part quality and functional strength) to qualify as end use products comparable to their off-the-shelf counterparts. These concerns (discussed below) are however being addressed by the AM community and indeed, according to Wohlers' survey, direct part production constitutes the largest portion (19.2%) of applications using AM.

A common feature to all 3D printed parts that has always been a distinguishing and tell-tale sign has been the visible layers that are evident from the building process. The layer thickness is a determining factor and is most prominently seen on curved geometry, resulting in a stair-stepping effect that negatively influences the quality of the final surface finish. For both powder- and extrusion-based processes, the surface finish quality is generally poorer on the underside of parts produced due to initial layering, particle size (in the case of powders) and removal of support structures (in the case of extrusion processes). Being aware of this inherent drawback of layer manufacturing, system developers have put a lot of effort towards improving the quality of surface finish by reducing layer thicknesses and particle sizes and improving software. In fact, the new file format for Additive Manufacturing, the AMF file that has been in development by the ASTM Committee F42 since 2009 and became official on May 2, 2011, incorporates curved triangles in order to improve geometric fidelity. By default, all triangles are assumed to be flat and all triangle edges are assumed to be straight lines connecting their two vertices. However, curved triangles and curved edges can optionally be specified in order to reduce the number of mesh elements required to describe a curved surface. The curvature information has been shown to reduce the error of a spherical surface by a factor of 1000 as compared to a surface described by the same number of planar triangles.

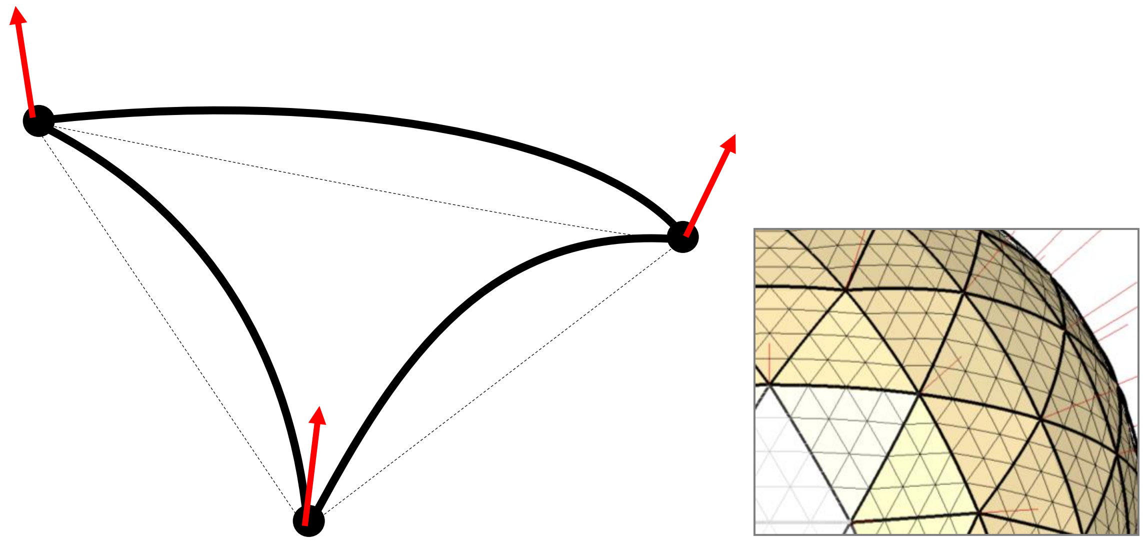


Figure 15 – Curved patch triangles using vertex normals

Concerns regarding functional strength have been mostly related to parts produced using the various metal fabrication processes (such as SLS, EBM, or SLM), most of which bind metal particles in powder form to create solid objects. The concern has been whether AM parts have comparable mechanical properties (especially in material density and strength) to parts produced from stock materials. In 10 years however, metals technology has advanced from almost nothing to thousands of production parts being produced annually. Over the years, a lot of research has gone into increasing part density and improving the overall material properties of parts produced using AM technologies to the point where metal fabrication processes are being used with confidence by the aerospace, automotive and medical industries – each of which require adherence to a high level of rigorous material standards. It is now possible to produce parts in a range of metals that are on par with wrought materials and exceed the properties of casting. Among the materials available are aluminum alloys, titanium alloys, nickel-based superalloys, and a range of steels.

Two further developments that may give parts produced directly by AM processes an added advantage is the use of functionally graded materials design as well as topology optimization.

Functionally graded materials design incorporates the use of multiple materials with different properties into one 3D printed part. Different material properties that could be beneficial include stiffness variation in polymers or using metals with varying heat transfer coefficients in for example, different regions of a mould design.

Topology optimization is a design method that lets mathematics determine where to locate material in a part. The method has been used for many years for preliminary concept design, but it was not until recently that these designs could be manufactured. This approach is resulting in radically different designs that reduce material, scrap, weight, and build processing time, yet offers the strength and stiffness required for the application.

Companies such as Airbus are very serious about using methods of topology optimization to design parts for aircraft. Airbus has found that the approach coupled with additive manufacturing, can reduce weight by 50-80%. This is significant when considering the hundreds of metal brackets that hold assemblies, such as the galleys and lavatories, onto the main body of the aircraft. Eliminating 220 lbs saves an airline $2.5 million annually in fuel costs for short haul flights, according to Dr. Phil Reeves of Econolyst.

Many organizations are also investigating the use of lattice, scaffold, honeycomb, and other types of structures that can dramatically reduce material and weight, while still producing strong parts. Increasing our understanding of how nature "manufactures" plants and animals will help us apply the use of topology optimization and organic structures to the production of AM parts.

So from the discussion above, it is clear that AM has improved to the point where parts can be produced directly for end use. Here are a few more successful examples where AM has been used for direct part production.

2.2.1 Fashion and Art Industry

3D printing has been used quite extensively in the footwear industry to produce color prototype models for visual confirmation of design. Only recently in this past year, has the fashion and textiles industry really started taking a more serious interest in 3D printing to produce functional shoes, accessories and even dresses. Some of the system manufacturers in the AM industry, (Stratysis and Materialise) have recognized this growing interest by partnering with fashion designers during the Paris Fashion Week in January this year [23]. Leading Dutch fashion designer, Iris van Herpen, teamed up with professor Neri Oxman from MIT's Media Lab to develop a range of 3D printed dresses that stretch the boundaries of this technology and utilize its capability to produce extremely complex patterns and geometry. Fashion designers are starting to recognize that the capabilities of 3D printing allow them to bring ideas to life that have not previously been possible with conventional textiles.

Figure 16 – 3D Printed skirt and cape designed by Iris van Herpen and Neri Oxman using Stratasys' Objet Connex multi-material technology

The challenge to create the 3D content needed for printing the apparel to fit the person has been made easier by improved software and 3D image capturing devices. In addition, pioneers in the fashion industry have pushed through by developing their own algorithms to design intricate 3D content around the needs and form of the user. Using the SLS process and nylon material, Jenna Fizel and Mary Huang from Continuum Fashion have developed the world's first 3D printed swimwear – appropriately named N12 after the material it's made from. The designers describe their swimwear as "fundamentally reflecting the beautiful intricacy possible with 3D printing, as well as the technical challenges of creating a flexible surface out of the solid nylon. Thousands of circular plates are connected by thin strings, creating a wholly new material that holds its form as well as being flexible. The layout of the circle pattern was achieved through custom written code that lays out the circles according to the curvature of the surface. In this way, the aesthetic design is completely derived from the structural design" [9].

Figure 17 – The world's first 3D printed bikini – the N12 [9]

Another example comes from a company in San Francisco, CA. Bespoke Innovations makes use of 3D printing to produce custom-made attachments to prosthetics for single and double amputees. Co-owner and industrial designer, Scott Summit, describes these attachment devices as "fairings", analogous to the coverings that provide styling to motor cycles. According to Summit, these fairings give the wearers a sense of self-worth and confidence as their customers form part of the design process to personalize the final product. Not all of their designs fall under the category of direct part production, as some undergo secondary post processing. Bespoke Innovations have however shown the impact that AM can make on this industry.

Additive Manufacturing has also not gone unnoticed by the movie and entertainment industry. Two recent examples have been the use of AM to produce parts of *Iron Man's* costume [11], as well as costumes used in Ridley Scott's *Prometheus* [12].

2.2.2 Jewelry

The design of and manufacture of a wide range of jewelry has also become quite common. Everything from simple bracelets made by children on Cubify, to professional work made by jewel designers using metal fabrication processes and sold on websites like i.materialise, Shapeways and Etsy. Depending on the final quality desired, in some cases further post processing is still done. In other cases, wax models are produced (with very high fidelity) and then investment cast to produce the final pieces. The key benefit that jewelers appreciate from using AM technologies, is the intricate complexity that they can achieve which may not have been possible using conventional techniques. In order to achieve these intricate designs however, jewelers now have to acquire CAD design skills in an industry that has traditionally been characterized by a high degree of hand skills. Software developers have recognized this need, and with options like Delcam's JewelSmith or Rhino's RhinoJewel, jewelry designers can produce their own 3D content for AM.

2.2.3 Medical Devices

From jewelry to medical devices, AM has definitely established itself as a very valuable tool for medical practitioners. Apart from medical models used for pre-surgical planning, one of the most successful examples where AM has been used to produce medical devices, is in the making of custom hearing aids by Phonak. An impression of the patients' ear canal is made and digitized to obtain a 3D CAD model. Then the SLS process is used to produce the housing shells for the electronic hearing aid equipment. Another growing application for medical devices is the manufacture and use of patient-specific instrumentation devices – which refers to custom drill- and cutting guides for orthopedic and dental surgeons to use intra-operatively during implant procedures.

Figure 18 – 3D printed dental cutting guide

Figure 19 – Patient specific instrumentation for knee replacement surgery [25]

2.3 Fit and Assembly

In several industries where prototype components are produced to fit and work as an assembly, AM has the capability to render such products during the early stages of product development. Assemblies of components can be 3D printed together in one operation and have the ability to contain moving parts. Alternatively, a variety of 3D print polymer materials have the flexure strength to snap fit together and act as a functional prototype. When using AM for fit and assembly components, it is however important to understand the tolerances and shrinkages involved for the process that is used in order to ensure that parts fit and function together as intended. In this regard, the different AM technologies have benefits and drawbacks that the designer should take into consideration when selecting the appropriate technology, depending on its intended purpose and quality required. Things to consider include the fact that the accuracy capability of the 3D printer may vary in each of its build axes, which would influence the choice of the build orientation [21], [22]. Also, the influence and removal of any 3D printed support material needs to be taken into consideration when the design contains complex internal geometries, especially if the support material removal is a manual process (as opposed to for example melting or dissolving away).

2.4 Prototype Tooling

In cases where larger quantities of parts are needed and it becomes economically unfeasible to produce all the parts by means of AM, product developers can consider prototype tooling as an alternative to produce small to medium batch sizes. In such cases, AM can be used to either produce the molds directly, or it can create patterns for manufacturing the prototype tooling through secondary processes. A choice between these two approaches will most likely be determined by factors such as the cost to produce the tooling, the batch size required, the desired quality of the final product, and the casting process and final materials needed.

2.5 Patterns for Metal Castings

If the desired final part material is a metal, these can be produced by means of 3D metal fabrication techniques such as SLS, SLM or EBM. Alternatively, developers may opt for a relatively cheaper option to produce their parts by means of investment casting where a 3D printed part will act as the lost “wax” pattern. The investment casting process traditionally makes use of patterns formed from wax material, which melts away to leave the ceramic mold to receive molten metal.

3 Current Trends

Many trends in additive manufacturing have come into focus over the past 12-18 months. Among them are advances in metals, the availability of new design tools, the expiration of key patents, and potentially explosive growth in the launching of new businesses related to additive manufacturing.

According to Wohlers [1], the following trends are impacting the current research, development, use, education, and strategies associated with AM technology. These trends coupled with recent growth estimates, provide a sense of where the industry is headed and how organizations and individuals might contribute to the future of the technology.

3.1 Serious Manufacturing

Additive manufacturing is now being viewed as a serious method of manufacturing. This was not the case a relatively short time ago. Boeing, for example, now produces 200 different parts with AM for 10 production aircraft platforms. An estimated 40,000 acetabular hip cups have been manufactured using electron beam melting, and about half have been implanted into patients. More than 10,000 metal copings are being manufactured daily for the production of dental crowns and bridges.

As companies qualify and certify AM processes and materials, we can expect many more types of parts being produced by additive manufacturing. The development of industry standards will also help accelerate the adoption of AM for the production of parts.

3.2 New Industry Standards

ASTM International F42 Committee on Additive Manufacturing Technologies is playing an instrumental role in the advancement of AM. As of April 2013, five industry standards had been published by ASTM, with many others in development. The five new standards are focused on AM terminology, testing, Ti-6Al-4V titanium alloy, and the AMF file format (as an alternative to STL).

These standards are important because they will help organizations qualify AM processes and materials faster and less expensively. Most industries do not fully mature without well developed industry standards, so the development of AM standards is an important trend.

3.3 New Design Tools to Obtain 3D Content

The emergence of basic design tools is allowing non-professionals to create parts and products. Products such as TinkerCAD (recently purchased by Autodesk [10]) and 3DTin are free web-based tools that can be used without downloading and installing software, as long as you are running a computer equipped with WebGL.

Autodesk's 123D suite of apps and Dassault Systems' 3DVIA Shape are available. They are also free design tools targeted at non-professionals. Trimble's SketchUp, previously from Google, is a product of choice for a range of users.

Co-design/co-creation tools are becoming increasingly available. Examples are the "creator" tools at Shapeways and custom design tools at i.materialise and Cubify.

3.4 DIY Maker Community

The do-it-yourself maker community is discovering AM and 3D printing. This group includes hobbyists, tinkerers, inventors, students, researchers, and entrepreneurs. Personal 3D printers are of particular interest to this group because they are affordable and often require assembly.

3D printers have been on display (and sold) at Maker Faire events sponsored by MAKE magazine and O'Reilly Media. Personal 3D printers have also been the focus of discussion at many local makers and user groups.

3.5 Personal 3D Printers

Personal 3D printer (i.e., systems for under $5,000) unit sales grew by nearly 300% in 2011. An estimated 23,265 units were sold, compared to 6,494 professional-grade, industrial AM systems. Never before has the AM industry experienced anything remotely close to this kind of unit sales growth.

These low-cost systems, with an estimated average selling price of $1,122, are reaching entirely new customers. With new users come new ideas that are leading to new product designs and businesses.

It will be interesting to see if growth of the personal 3D printer market will mimic that of the market for personal color inkjet printers. That market segment expanded dramatically with the increase of digital imagery and content. The online 3D model libraries offer content to feed 3D printers. However, the lack of design and CAD tools that match the ease of use of programs like Photoshop, coupled with the lack of design knowledge, could limit market penetration at the low end of the cost spectrum. But printer manufacturers have recognized this growing trend and the need to make 3D imagery and content more easily accessible to the personal 3D printer market.

During a panel interview at a recent 'Expand' event hosted by Engaget in March 2013, experts drew a comparison between future 3D printers and today's desktop printer and the software related to each [7]. Hod Lipson, Professor of Engineering from Cornell University and Avi Reichental, President & CEO, 3D Systems, were in agreement that the future 3D printing user will not be interested in *how* the 3D printer works as much as *what* they can produce with it. For the same way in which word processing software such as Microsoft Word totally democratized the editing and publishing world, the AM industry is still waiting for the release of similarly powerful 3D content software that will further unleash the potential of 3D printing for the masses.

3.6 Explosion of New Businesses

The advancement of AM is creating vast opportunities for individual entrepreneurs, as well as entrepreneurs within organizations of all sizes. The pieces are falling into place for a 21st century "Gold Rush" in design and manufacturing. Thousands of new companies, and new types of products and business models, will emerge over the coming years.

Who would have guessed that Shapeways would be producing tens of thousands of parts per month after only four years in business? In the month of March 2012, for example, the company shipped 100,000 parts consisting of 27,000 products to customers. Shapeways shipped a total of 750,000 parts in 2011. Other businesses (and the list continues to grow) that are providing similar services include:

- 3D Systems' Cubify – www.cubify.com

- MakerBot's Thingiverse – www.thingiverse.com
- Materialise's i.materialise – www.imaterialise.com
- Ponoko – www.ponoko.com
- Kraftwurx – www.kraftwurx.com
- 3D System's Freedom of Creation – www.freedomofcreation.com
- The 3D Printer Experience – www.the3DPrinterExperience.com
- MakeXYZ – www.makexyz.com
- Makershop – www.makershop.co

The way in which these companies are offering their services are challenging the status quo of traditional business models. The culmination of both AM hardware (for manufacturing) and software (internet and web applications for communication) has matured to the point where mass customization has become an option with real potential. Anyone in the world can upload their 3D model and these providers will create it for them. But the real business model is set in motion when the designer decides to post their creating available for sale on the service provider's website. In this way, designers can essentially bring a product to market with no risk. There is no physical inventory that ties up cash flow anymore, and they don't even have to make sure that there is a market ready for their product. If they sell one, that's great – if they sell 10,000 then all of a sudden they have a passive income model. And that radically changes the economy!

Usually to bring a product to market, takes at least a year, and then one has to find the manufacturer and the investor. Now we have this explosive technology where everything is made just for the individual, but at the price and quality of something one could buy in a store. This could be a scary technology for some companies, because what implications does this have for seasonal products? And with an infinite inventory, what does that mean for scarcity, which is one of the core tenants of so many industries.

In some ways however, these industry developments have a parallel similarity to social media or other tools of engagement, where companies were cautious at first to consider the prospects of letting consumers co-create with them. However in embracing consumer involvement and managing the process, new possibilities can be leveraged from creative collaboration. As the market changes, we may need to stop thinking that one needs to reach 100,000 or a million people for something to be successful. But instead, customization challenges us to think about design and production for the individual.

3.7 Labs with 3D Printers

In 1983, Colorado State University established a hands-on lab with 20 IBM PCs equipped with AutoCAD. A university credit course on AutoCAD was offered, which is believed to be the first worldwide. Previously, a university might operate one or two mainframe or minicomputer-based CAD systems and few students were able to touch them.

History is beginning to repeat itself with the popularity of personal 3D printers. Educational institutions are purchasing machines in quantities of 5, 10, and 20 at a time. An "Idea 2 Product" lab with 20 personal 3D printers was launched in 2011 by Professor Deon de Beer of Vaal University of Technology (Vanderbijlpark, South Africa). This was an industry first, and others are following his lead.

In addition to the proliferation of personal 3D printers at educational institutions, local community libraries have started to invest in low-cost 3D printers and making these available to the public. Since late 2011, when the Fayetteville Public Library received widespread media attention for its hackerspace[26], 3D printers slowly began appearing in libraries around the world, particularly in the United States. Riel Gallant, a Library and Information Studies graduate from Dalhousie University, Canada, has recently reported that 51 libraries across the world (75% of which are in the United States) have been found to have a 3D printer within their facilities [27]. One of these libraries includes the Sacramento Central Library in California. The availability of 3D printers in public libraries is a significant further development towards making this technology more accessible to the general public.

3.8 Expiration of Key Patents

When the original fused deposition modeling (FDM) patent by Scott Crump, FDM inventor and co-founder of Stratasys, expired, it allowed for the RepRap open-source project and many RepRap-like systems to become commercially available. That eventually led to the more than 20,000 personal 3D printers that were purchased in 2011.

The last of the selective laser sintering (SLS) patents from inventor Dr. Carl Deckard and the University of Texas at Austin (patent 5,639,070) will expire in June 2014. Already, bright individuals have discussed how they might approach a lower cost and possibly smaller alternative to the current laser-sintering machines protected by this patent. By mid 2014, we can expect to see several new developments based on laser-sintering technology.

As the industry ages, additional patents will expire, allowing creative individuals and organizations to capitalize on the opportunities that the expiration will create. These new systems, and the materials available for them, will make it difficult for established system manufacturers to lock customers into purchasing high-priced materials.

3.9 New Types of Machines

The invention and development of new AM process technology is ongoing. Methods which are potentially faster than laser sintering, such as Loughborough University's high speed sinter, can sinter an entire layer at once. Printoptical technology from LUXeXceL Group B.V. is capable of producing parts with optical clarity, such as lenses, without the need for any post processing.

New types of machines will be developed. Some will be designed for general-purpose prototyping and manufacturing applications, while others will be targeted at niche markets with specific materials and specific sizes and types of parts.

3.10 Tooling from AM

In the 1990s, many individuals and organizations developed processes and materials, or used existing ones, to make molds and dies. The use of AM to produce injection-mold tooling was of most interest. More than a dozen efforts were underway over a period of more than a decade. However, nearly all of them failed, which tarnished the image of AM in the tooling industry. We are now seeing a slow and deliberate resurgence in the use of AM to produce molds, dies, and many other types of tooling. When matched with the right job, AM tooling can provide the best route. Some companies are finding significant savings, especially when integrating conformal-cooling channels to reduce plastic injectionmolding cycle time. Hybrid machines that add and subtract material, such as Matsuura's Lumex Avance-25, could make the concept even more compelling.

3.11 Mainstream Press

The technical press has long covered the subject of additive manufacturing. The mainstream press has "discovered' it recently and cannot seem to get enough of it. To many, it is now fashionable to talk about the technology and how it could change manufacturing forever. Almost everywhere you turn, someone is talking or writing about it, whether it is a blog, web article, or printed story.

The April 21, 2012, issue of *The Economist* included a special 14-page insert with eight articles on the digitization of manufacturing. Most of them discuss AM and 3D printing, some in great depth. Three days later, *Bloomberg Businessweek* published a multi-page story entitled "3D Printers: Make Whatever You Want." It discusses the technology's history, its many applications, and where it's headed. Television news programs are also covering the subject, and we can expect a lot more coverage in the future.

3.12 U.S. Government

For many years, the U.S. government has supported AM in the form of National Science Foundation grants, Small Business Innovation Research grants from many agencies, Department of Defense contracts, and other programs that have provided financial assistance. In March 2012, the White House announced a proposed investment of $1 billion for a National Network for Manufacturing Innovation involving up to 15 institutes across the U.S. A pilot institute focused exclusively on additive manufacturing was launched using $45 million of existing resources from the Departments of Defense, Energy, and Commerce, and the NSF. As already mentioned in Chapter 1, the Obama administration has continued to roll out this funding program with the announcement of three further manufacturing innovation institutes to be federally funded with $200 million across five agencies – namely Defense, Energy, Commerce, NASA, and the National Science Foundation. These exciting developments will continue to support the growth of the AM industry and allow new opportunities to emerge.

Recommending the Way Ahead

Part 2

Part 2 – Recommending the Way Ahead

4 Future Trends

A number of interesting developments will help shape the future of additive manufacturing. The following builds on the trends presented previously and offers some exciting possibilities for the future of AM [1].

4.1 Far More Demanding Applications

As users demand more from AM, developers will deliver more advanced processes and materials. Aerospace, medical, dental, and some consumer-oriented companies are investing heavily and pushing the limits of AM. Many see it as a solution to provide high-value, high-margin parts and products.

Robet McEwan, general manager of Airfoils and Manufacturing Technologies at GE Aviatior, said that in our lifetime, at least 50% of a jet engine will be made by AM. This statement is profound, but it could become a reality if the right people and organizations are determined to make it happen.

4.2 Printed Batteries and Electronics

A new frontier will be the printing of battery materials and electronics that conform to a product's shape. In a single operation, the housing of a product would be printed with integrated electronics and power storage. The impact this would have on handheld electronics and other devices is tremendous.

In 2005, Sandia National Laboratories and the University of Texas at El Paso demonstrated the printing of a 3D circuit. Netherlands-based TNO, as well as the Lawrence Livermore National Research Laboratory has since developed a number of circuit printing technologies and has printed a copper circuit and integrated housing in a single operation.

4.3 Legal Issues

The relative ease of 3D scanning shapes and reproducing them by AM creates opportunities. However, it will also generate many legal problems. The cost of 3D-scanning products continues to decline as the $150 Microsoft Kinect device becomes an option. Inexpensive apps also turn an iPhone into a 3D scanner.

Legal liability will also become an issue as more people enter the design and manufacturing business. Suppose a small web-based company sells an electronic design of a new product to someone. They change the design and sell it to another consumer, who then performs some additional changes to the design before having someone print it for them. In this scenario, who can be characterized as the designer, manufacturer, or distributor of the product in the event of injury or loss? This will also impact the insurance companies as new products, business models, and distribution channels emerge.

4.4 Workflow Management

The use of AM for production quantities will cause many companies to rethink and redevelop the flow of new product data in organizations. When companies can begin to manufacture almost immediately after a design is complete, it will disrupt standard supply chain practices that often take weeks or longer.

Being able to manufacture many different types of products simultaneously will also cause companies to consider the best way to get products through their company. Packing and optimizing build chambers, coupled with the IT infrastructure needed to be efficient, will become critical.

Post-processing will become a major consideration. The goal at most companies will be to automate the removal and cleaning of support material, as well as finishing, coating, heat treatment, and a host of other possibilities.

Using the same process for both prototyping and manufacturing will be a welcomed improvement to most companies, but it could present capacity and priority issues during peak times of product development and manufacturing.

4.5 3D Printers for Children

One of the largest consumer market opportunities is children. A significant number of the seven billion people worldwide are kids 5-10 years of age. Most kids like to use their imagination and create objects. Many enjoy playing with computers, video games, and smart phones – all of which are capable of creating 3D content. As the cost of personal 3D printers is driven downward, and the number of online 3D printing options expands, children will have almost endless opportunities to print their creations.

Origo is a Dutch-based startup company that was in the early stage of producing a low-cost, safe, and easy-to-use 3D printer for children. They unfortunately seem to have abandoned the project for now, but it should not be surprising if we see similar projects come to life on Kickstarter or through any number of other funding mechanisms.

5 Recommendations for Technology Transfer

5.1 General Model for Technology Transfer

Given the background of new developments described in Chapters 1 to 4, this chapter looks at how the CACT can align its future strategies to the rapidly changing AM industry, keeping in mind its current goals and constraints. These recommendations are framed along three sequential partnership groups that are facilitated by the CACT, namely high schools (for early exposure), college students and faculty departments (to build skilled labor), and industry partners (to serve needs for *making it in California*).

Technology transfer in general is a process that can be encouraged and fostered, but it requires the right environment with support and a good understanding of the different role players in order to flourish successfully. Technology transfer involves the transfer of both *information* (in the form of education and workforce development) as well as innovation (in the form of licensing new technology to startups). Several models exist that describe the interaction and transfer between the public (academic) and private (industry) sectors. During a Tech Transfer Symposium back in May, 2010, Linda Katehi, Chancellor of the University of California (Davis) presented a model which she referred to as the *Continuum of Innovation.* She described how this model (shown below) often exists at universities, and that it is in her opinion, a flawed model.

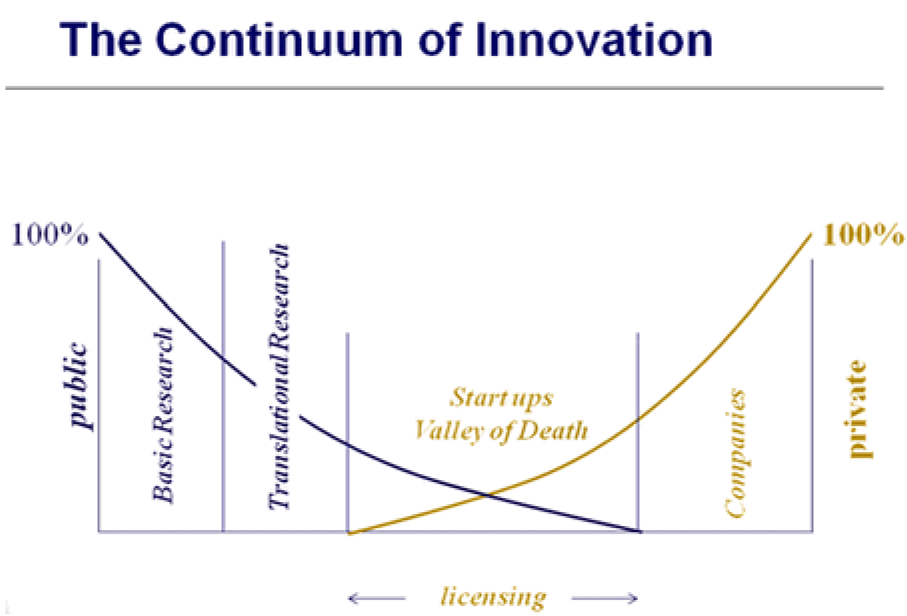


Figure 20 – The current way research and innovation is often handled at universities [13]

According to this model, the University engages in basic research, moving on into translational research, before turning the innovation over to start-up companies. It is in this hand-off period that there is much risk and uncertainty because start-ups frequently fail due to a variety of different reasons. Katehi explains [13]:

> *"Universities find it very difficult to be successful in technology transfer because I believe they have adopted business models that have not been sustainable. It is very costly for an institute to go and file for patents and yet there are not very clear feedback loops that bring back to institutions to sustain these operations. So Universities quickly find it extremely expensive to sustain their own tech transfer offices, and they are under extreme pressure to produce funding early as opposed to making investments toward those activities and seeing those investments as long term."*

Community colleges like Sierra College perform a somewhat different role than universities in that they do not focus on performing basic research. That being true, this remains a good point of departure from which to describe the potential role(s) that community colleges can fulfill and where to capitalize on their areas of emphasis. More on this will be discussed shortly.

Referring to it as the *New Innovation Ecosystem*, Katehi concludes that a new model is required, which is illustrated by the image below.

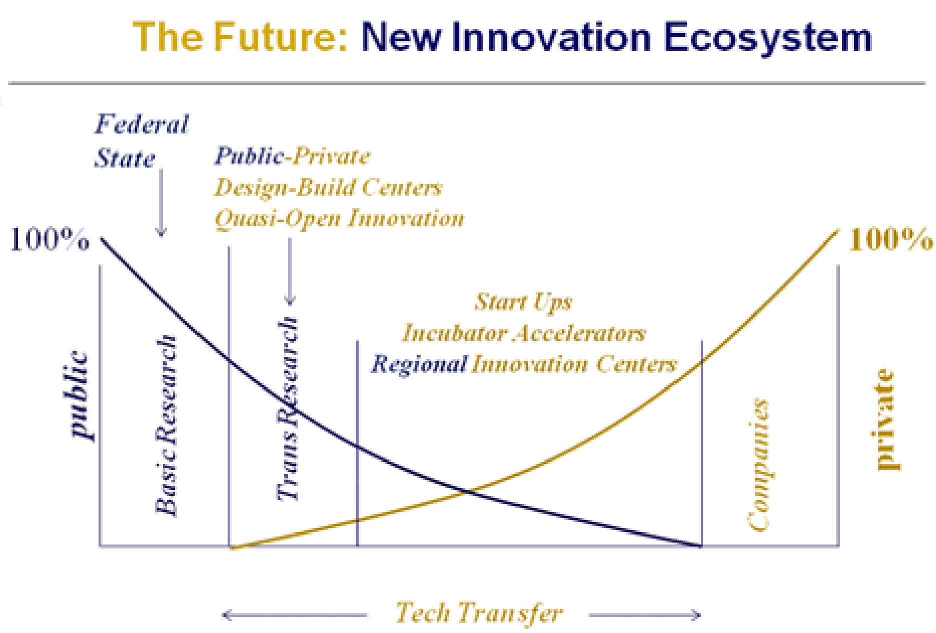


Figure 21 – A proposed model for improved technology transfer [13]

In this model there is a public/private collaboration specifically around the area of translational research, and assistance to start-ups from incubators and innovation centers. She also suggested future efforts to develop a national framework for translational research, create design-build innovation centers, understand the innovation ecosystem and develop a sustainable business model, consider quasi-open innovation models, and expand public-private collaborations to fund translational research.

5.2 Proposed Sierra College CACT Model for Technology Transfer

Given this foundational viewpoint towards a model for technology transfer, and the context within which community colleges focus their attention on teaching activities downstream from basic research results, Sierra College CACT may still find this model appropriate to apply to their technology transfer activities. Taking a closer look, Katehi's model can be refined to describe the role that community colleges can play in managing this transfer of technology, and is shown in the diagram below.

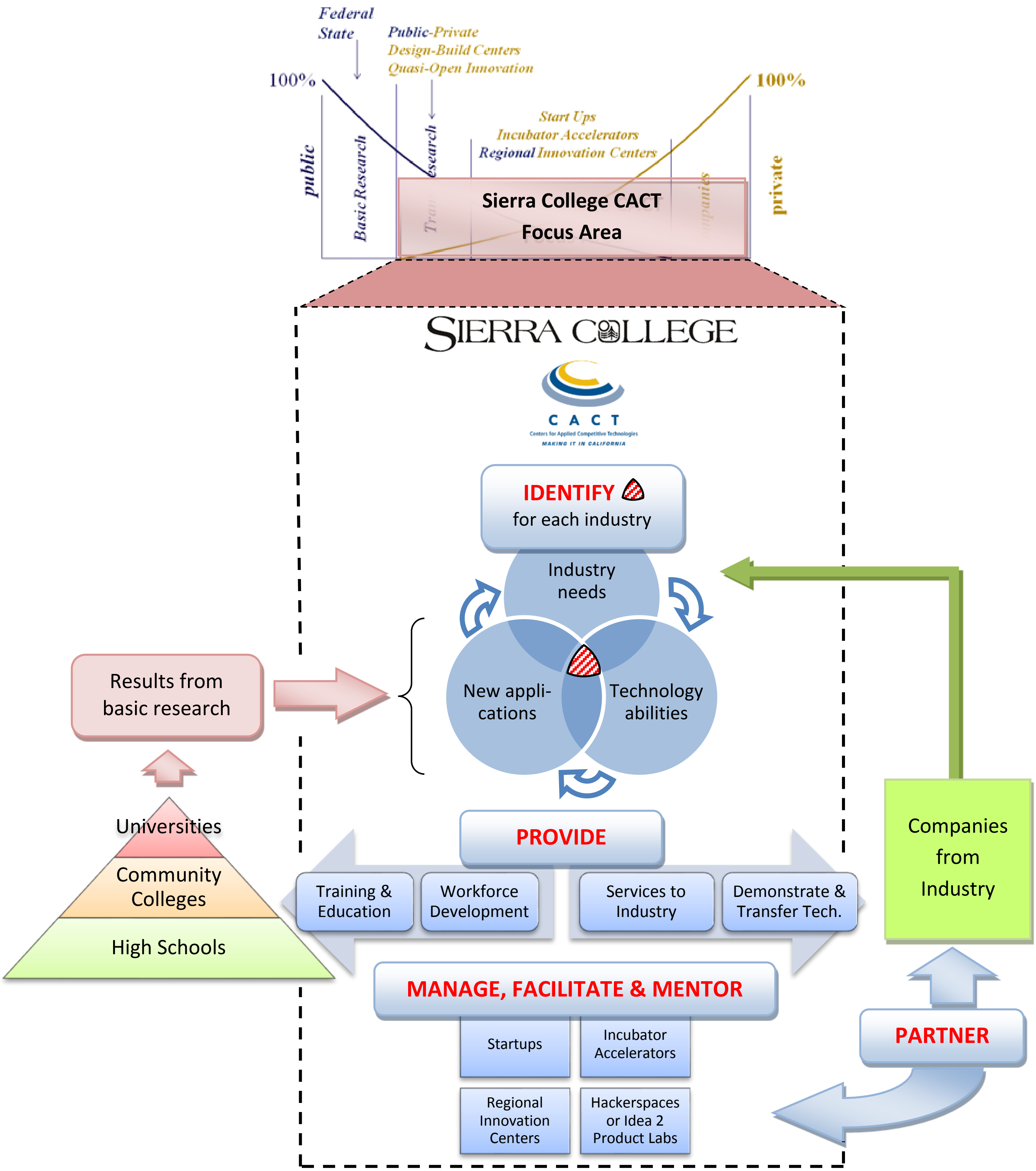


Figure 22 – Proposed Sierra College CACT model for technology transfer

Community colleges fulfill a unique role in facilitating workforce development and education while at the same time sharing close relationships with industry partners. These close relationships with industry partners give community colleges the ability to adjust their curriculum and apply new technologies in a way that will train students to be well prepared to meet the needs in industry. According to the model shown above, CACT should seek to:

1. **IDENTIFY** for each relevant industry, the focal point of three key drivers that will bring a significant improvement to that industry. The first of these are identified by developing industry wide relationships while the second and third often result from basic research at universities (or of course also from industry research and development results). Therefore, seek to identify:
    a. The most prominent industry needs,
    b. Abilities of suitable technologies that can be used to solve these needs, and
    c. New applications that become possible with every new improvement to the technology (e.g. when a new AM material becomes available, it automatically opens up new areas of application).
2. **PROVIDE**
    a. Training and education to high school (through awareness programs) and college students (through appropriate curriculum) – thereby assisting in workforce development.
    b. Services to industry and demonstrate technology transfer through workshops and joint project ventures.
3. **PARTNER** with various companies from industry by building active relationships. These relationships will prove fruitful in the long run to identify industry needs and to garner support (sponsorships or otherwise) for new joint ventures.
4. Inevitably, new innovation will result from all of these activities and collaboration. The CACT should seek to create mechanisms to **MANAGE, FACILITATE AND MENTOR** such new innovation.

5.3 Proposed New Facilities

The facilities that Sierra College CACT currently hosts with regards to design and product development for AM, are a number of CAD workstations, a 3D laser scanner (NextEngine), and two Dimension 3D printers from Stratasys – one of which is currently on loan at Oakmont High School. Demand on these printing facilities is currently relatively low, but is considered to increase with higher utilization in curriculum programs and more marketing exposure to industry. In order to prepare for this growth and to remain relevant with the latest developments in this industry, it is recommended that Sierra College CACT considers additions to their current facilities.

Some educational institutions have opted for purchasing higher end AM machines that are typically coupled with research programs and other curricula. Taking into consideration the mandate, focus and resources of Sierra College however, an approach to reach more students with lower cost facilities is rather recommended. One model that may be considered that originated from South Africa and has successfully been applied at other academic institutes; is the model of so-called Idea 2 Product Labs.

5.3.1 Idea 2 Product Labs

Based on a model similar to FabLabs that was originally conceived by Neil Gershenfeld at MIT, the Idea 2 Product Labs aim to provide exposure to creative technologies like 3D printing and scanning, coupled with CAD design to new learners of these technologies. The original Idea 2 Product Lab was conceived in 2011 by Prof. Deon de Beer at Vaal University of Technology (VUT), Vanderbijlpark, South Africa. The lab acts as an Innovation Centre to support getting innovative new ideas into physical form. It hosts a number of CAD stations along with several low-cost 3D printers that is open to students from the university as well as people from the public to utilize. These are used for hands-on learning, experimentation, invention, and new product development. The primary goal of the labs is to offer opportunities for professional and economic development, especially in underdeveloped regions of South Africa and other parts of Africa.

Figure 23 – Students at work in the Idea 2 Product Lab at VUT

Apart from the lab at VUT, Prof. de Beer also created a smaller I2P lab with two 3D printers in a rural area of South Africa. He has ordered 70 additional 3D printers (20 have been received thus far) for four new I2P labs at educational institutions that are similar to community colleges here in the U.S. In parallel, he is creating I2P labs at three VUT satellite campuses and two more at science centers.

There are big future plans for I2P labs. Prof. de Beer envisions I2P labs across the African continent and already has tentative plans for labs in Zambia, Mozambique, and Botswana. In the meantime, he sees the potential for labs at up to 22 universities, 50 community colleges, 25 private institutions, 20 science centers, and many secondary and primary schools in South Africa. He is also gaining support for the first I2P 2Go mobile unit that would take 3D printers on the road to remote areas (see Figure 24).

I2P Labs are already starting to spread to other countries of the world. Professor of Mechatronics, Olaf Diegel at Massey University in Auckland, New Zealand, has started an I2P lab. In June, Colorado State University (CSU) will also officially be launching their I2P Lab facility. David Prawel, a senior research scientist in the Department of Mechanical Engineering at CSU, has opened the I2P Lab to the community so anyone can use their 3D printing facilities. The laboratory is hosted by the Engineering department and it is staffed by current and graduated engineering students. The lab charges a nominal fee for materials and maintenance. Software and equipment are funded by contributions from Autodesk, Lulzbot, Advanced Manufacturing Enterprises, the Mechanical Engineering Department and by CSU's students through the university's Student Fee Review Board [14].

Figure 24 – Idea 2 Product 2Go concept, courtesy of Vaal University of Technology

The potential impact that such I2P labs could have is almost beyond calculation. Each lab could introduce hundreds of people of all ages to CAD, design, product development, and manufacturing. This could lead to a dramatic increase in new ideas, new products, and new mini economies that would lead to improving economic conditions in underdeveloped regions.

5.4 Reaching Out to Surrounding Schools

Studies have shown that students who are educated in AM processes are among the first to bring the advanced and hands-on technologies to their employers. Based on the data provided by educational institutions, a growing number of institutions are integrating AM technologies into their curriculum and laboratory practices [1]. However, some state institutions are facing budget cuts and limited equipment and supply funds. Even so, using AM to develop new products in a hands-on way is becoming essential in most engineering, art, and technology curricula. Educational institutions are challenged to create new curricula and acquire equipment, software and materials. Yet declining prices of currently available AM systems make them increasingly attractive for more preschool through four-year college (P-16) institutions to practice AM technologies in their science, engineering, and technology programs.

Justin Kirby reported in January about a pilot project in some schools of the United Kingdom that will investigate the use of 3D printing in schools for teaching mathematics, physics, computer science and engineering and design [16]. The U.K. Department of Education is supporting this project and 21 schools have been selected from 40 top performing math and science schools who submitted short proposals on how they would use the 3D printers across the relevant subject areas. The schools all received a Makerbot printer, consumables and access to training. The project will run until September 2013 (with regular updates from schools), and is being managed by the Institute of Physics (IoP) and the National Centre for Excellence in the Teaching of Mathematics (NCETM) with support from the Design and Technology Association.

Sierra College CACT has also taken initiatives to assist with expanding AM technologies to surrounding high school Career & Technical Education programs through Sierra STEM Collaborative [15]. Regional high schools that have benefitted from their direct involvement in the form of sponsorships and collaboration include Rocklin High School, Del Oro High School, and Oakmont High school. The CACT also collaborate with signature high school CTE programs to produce AM parts. For example, Sierra College prints award models, designed by the Rocklin High School Engineering Support Technology program students, for the NASA Lunabotics Mining Competition – an international event held at the Kennedy Space Center in Florida.

The main emphasis in allowing young learners access to AM technologies, is to provide them with early exposure to benefit them in long term progress and innovative thinking. So any efforts to provide such opportunities to this young generation should prove to be beneficial. Giving students the opportunity to share with one another quickly develops into a peer-to-peer learning experience. An example of this phenomenon is clear from the fifth annual Student-to-Student Conference that was held earlier in May this year in Santa Cruz, CA [17].

Another idea for reaching out to young learners has been demonstrated by Manuela van den Bos, a teacher of the Chr. Jenaplan Morgenster Elementary School in Geldermalsen, The Netherlands. This primary school has launched "De Alant", a gifted education program for children between 8 to 12 years old. The school gives children difficult projects to teach them how to work with challenges. One of the tasks is to build an Open Source 3D printer. The 3D printer provided is a kit from Ultimaker and the children need to put it together. They are divided into groups and everyone builds a part of the 3D printer and in the end they work together to complete it. Van den Bos was very excited about working on a 3D project with primary school students and she recommends that all schools start such a project. What have these kids learned from such a program? "They learn how to work together in a team, they learn how to look for solutions, either from online resources, or approach to specialist asking for advice. These are all new for them." said Van den Bos [18].

Figure 25 – Learner from "De Alant" program putting together an Ultimaker 3D printer

5.4.1 Formal Outreach Programs

Tennessee Tech University, Alignment Nashville, Pencil Foundation, Adventure Science Center, and Metro Nashville Public Schools continue their work on an NSF Innovative Technology Experiences for Students and Teachers (ITEST) grant. The project, titled Art2STEM, recruits and encourages seventh- and eighth-grade underdeveloped and underserved girls to select Science-Technology-Engineering-Math (STEM) career academies in their high school education. Project coaches and mentors use AM methods as a tool for their project deliverables. Models are created by the students and built at the Tennessee Tech University's Remotely Accessible Rapid Prototyping Laboratory.

The National Science Foundation funds two Advanced Technological Education centers associated with AM. One is the National Resource Center for Materials Technician Education (MatEd), housed at Edmonds Community College (Lynnwood, Washington), and the second is the National Center for Rapid Technologies (RapidTech), housed at University of California-Irvine. The two have partnered to develop new AM core competencies and curriculum. These competencies and curricula are based on newly developed global ASTM industry standards.

Project TEAM – Technician Education in Additive Manufacturing – takes advantage of an unprecedented opportunity in which education is involved at the ground level of global AM standards development focused on technician education. Project TEAM has two overarching goals. The first is to participate at the ground level of global AM standards development by providing technical and educational input in the areas of terminology, test methods, processes, materials, and design that facilitate the creation of AM core competencies. The second goal is to improve technician education and training programs by translating AM standards into core competencies and then assisting educators with integrating them into manufacturing technician programs.

A partnership between the Commonwealth of Virginia, University of Virginia and the City of Charlottesville has led to the creation of CED (Commonwealth Engineering and Design) Academy at Buford Middle School, a new type of school built specifically around project-based learning with the help of new technologies such as 3D printing in K-12 education. The new program, which opens in August 2013 after a $3 million renovation, will have one 3D printer for every 4 students in a classroom [19]. Faculty and students from UVA's Schools of Engineering and Education are working together to develop and test new curricula for critical STEM (Science, Technology, Engineering and Mathematics) education that makes use of 3D printing. One of their first successes was a project in which middle school students designed and built a fully functional speaker. Teams were broken into two halves – one to design and test a high frequency tweeter and another to design and test a low frequency woofer – and then at the end of the project the two teams were required to combine the two parts into one integrated speaker.

5.5 College Students, Faculty Members and Universities

The increasing number of institutions that include AM education and research indicates the acceptance of the technology. Areas of focus are design, modeling, simulation, engineering, architecture, and construction. Additional areas are art, biomedicine, dentistry, defense, genetics, nanotechnology, pharmaceuticals, archaeology, forensics and photonics.

Over the years, institutions of higher education worldwide have played a crucial role in all aspects of AM-related education and research activities. In design, engineering, technology, and art, it is an exciting alternative to virtual modeling because students can actually see, hold, and interact with their projects.

AM systems are used to teach curricular concepts to groups ranging from junior high and middle school students to post-doctorate scholars. Many colleges and universities have one or more additive processes in-house or enjoy access through another organization. Sierra College CACT has collaborated with the college CTE and academic programs by placing a Dimension FDM machine and a NextEngine laser scanner in the CAD lab to increase accessibility. The CACT provides technical assistance in running parts on the machine, and providing maintenance services.

AM activities at Sierra College can be further expanded by inviting other faculty members from different departments to experiment with new applications for 3D printing within their disciplines, and present their students with new and challenging ideas. Here are a few ideas for a selection of relevant programs:

- **Agriculture** – Geographical mapping of vegetation resources models (color printing required)
- **Anthropology** – Recreation of bone and other models from CT scanned data of artifacts.
- **Art** – Various creative ways to create intricate 3D art sculptures and industrial designs.
- **Automotive technology** – Prototype models of various engine components, including assemblies that will assist in demonstrating interaction between components.
- **Biological Sciences** – Polylactic Acid (PLA) is a water-soluble material used for support structures on FDM 3D printing machines. It can also however be used as the main build material to construct 3D scaffolds for tissue engineering applications. Experiments with other biodegradable polymers can be done using the FDM technology.
- **Chemistry** – 3D representations of complex molecule structures can be produced using the 3D printer. Ideally, a color printer would be more appropriate to represent various color standards for compounds. Polymer parts from the FDM machine can however be painted after printing.
- **Construction Technology** – Various configurations for construction can be tested by printing scaled physical models in 3D. Students can for example, investigate the various constructs involved in bridges or other load bearing designs and test their models by applying physical loads.
- **Drafting and Engineering Support** – 3D Models can be produced to assist students to more easily visualize their 2D drawings.
- **Earth Science** – Once again, geographical mapping from GIS data (in color) can assist students to visualize models of earth terrain or mineral deposits.
- **Education** – Students from this department need to be made aware of how 3D printing can be another tool that they can use to reach learners. As 3D printing is becoming more prevalent in middle and high schools, it becomes all the more relevant for future teachers to be trained in using this technology, especially in the CTE focused programs.
- **Engineering** – 3D printing is an essential tool within the engineering disciplines and should be incorporated within all design and manufacturing related subjects.
- **Environmental Studies and Sustainability** – 3D printing is being shown as an increasingly viable option for small business entrepreneurs. In addition to these business models that contribute to sustainable economies, efforts are already underway (Filabot and others) to show how polymers (from plastic milk cartons among others) can be recycled into extruded filament ready to be

used on 3D printers. In this way, improving the environment through recycling and adding value to waste material.

- **Fashion Design and Merchandising** – This is an exciting field where 3D printing is expanding into rapidly. Students from this department should gain experience in designing new fashion items such as jewelry, footwear, accessories and even dresses (as described in Chapter 2 above).
- **Geography and Geology** – See Agriculture and Earth Science above.
- **Health Education and Health Sciences** – 3D models of patient anatomy can be constructed from CT scan data. These models can be used for education, communication, practicing and planning procedures, or preparing implants or other devices. Alternatively, 3D patient-specific tools can also be produced by 3D printing to be used as custom cutting and/or drill guides.
- **Marketing** – Students from marketing should be made aware of how prototype models can be produced by means of 3D printing for them to use during marketing meetings or new product launches.
- **Mathematics** – This discipline can utilize 3D printing to bring complex 3D geometric features to life and more easily visualize the effect of changing variables in an equation. This field is also important in the fact that mathematical equations are used more frequently to produce complex geometric features and lattice structures as opposed to conventional CAD software.
- **Nutrition and Food Science** – It may be interesting for these students to be made aware that there are efforts underway to use 3D printing to directly produce food products. In the confectionary industry, experiments have been done to make use of 3D printing to decorate cakes and other items. More serious research by Hod Lipson's group (at Cornell University) is looking at how to 3D print food items containing a balanced source of nutrition.
- **Real Estate** – 3D printing is used to produce models of architectural display models.
- **Skill Development** – 3D printing and CAD design is in itself a very relevant skill to obtain.

5.5.1 The challenge of developing new formal curriculum for AM

As the AM industry continues to become more accessible and expands with its new applications and software, educational institutions face the challenge of providing guided exposure and training to new students (that are becoming younger and younger). The challenge is therefore set for the AM community to formalize a set of curricula that can serve to provide a foundation for new learners of this technology. This is a challenging concept due to the fact that the technology continues to develop improvements at such a rapid pace. The AM community has however, already recognized the need to provide such a framework for this growth, which was the basis for initiating the ASTM International F42 Committee on Additive Manufacturing Technologies that has been focusing on defining a basis for terminology and other standards for this industry. Glenn Bull, professor and co-director of the Center for Technology and Teacher Education at the University of Virginia, can attest to the challenges that he and his colleagues face while trying to develop new curriculum for learners [19]. Prof. Bull however believes that every school in America could have a 3D printer in the classroom in the next few years.

A media resource that has just recently been published in May 2013 and made freely available should assist in developing such curriculum. The book called *Low-cost 3D Printing for Science, Education and Sustainable Development* has been authored by Enrique Canessa et. al. and has been published by The Abdus Salam International Centre for Theoretical Physics, in Italy [20]. It contains 200 pages of information regarding the basics of 3D printing and presents case studies with examples of how this technology has been used in science, education and sustainable development. It is *highly recommend* anyone interested in this subject matter to study this book for further information. It can be downloaded for free at http://sdu.ictp.it/3D/book.html

International collaboration in the efforts for developing educational curriculum standards and content will be a valuable endeavor. Potential electronic resources that can assist with this collaboration to develop and later distribute such curricula could include:

- **The ASTM International Committee F42 on Additive Manufacturing Technologies** – Tasked with developing standards for terminology and material properties, output from this group may form the foundation of future curricula.
- **TEDEd** (www.ed.ted.com) – This platform allows users to take any useful educational video, and easily create a customized lesson around the video. Users can distribute the lessons, publicly or privately, and track their impact on the world, a class, or an individual student.
- **Sekoia Learn** (www.sekoialearn.com) – Similar to TEDEd in the fact that it provides a platform for educational video. It is still in its startup phase and scheduled to launch in September 2013. It does however seem to indicate some more functionality than TEDEd offers in terms of its course structure and student performance tracking.
- **Khan Academy** (www.khanacademy.org) – A popular educational resource containing thousands of videos explaining complex subject matter in simple terms.
- **LinkedIn Groups** (www.linkedin.com) – This and other social media websites can be used to form collaborative groups around specific subject matter. There already exist a number of LinkedIn groups with active participation from various worldwide leaders in the AM industry.

5.5.2 Californian Institutions with Large Scale AM Capabilities

Several universities have developed AM processes that have formed the foundation of commercially available systems and materials. Examples are MIT's 3D printing (3DP), The University of Texas at Austin's selective laser sintering, Cornell University's Fab@Home, and the University of Bath's RepRap project. In California, there are a number of institutions that have invested in large scale AM. Below is a list of three of these describing their main focus and capabilities.

Loyola Marymount University (LMU)

The Rapid Prototyping Laboratory is used extensively for instruction and R&D. The laboratory supports product development efforts among students and faculty using an FDM system from Stratasys and a Spectrum Z510 from 3D Systems. Current research projects focus on improving the strength of the ABS 400 material and studying the surface roughness and accuracy of reverse-engineered parts.

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Saddleback College, Irvine, CA (RapidTech)

RapidTech is the national Center for Rapid Technologies, supported by the National Science Foundation. Its equipment is spread across two locations but most is located on the University of California-Irvine (UCI) campus. RapidTech's NSF goals focus on the development of pathways related to AM and overall leadership in the AM field. Also, it continues to support community college and UCI student projects, faculty research grants, and other on-campus research activities. RapidTech has a considerable amount of interaction with private industry in the areas of materials, hardware, and process improvement.

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University of Southern California
Several NSF- and NASA-funded AM works, as well as related CAD issues, are under research and development at the Center for Rapid Automated Fabrication Technologies (CRAFT). The centerpiece technology at CRAFT is the contour crafting mega-scale fabrication process. Contour crafting is a process that produces large-scale parts additively from 3D computer models. With contour crafting, computer control is used to take advantage of extrusion and the surface forming capability of troweling to create smooth, freeform surfaces.

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5.6 Industry Partners and New Clients

Apart from Sierra College CACT's involvement to support career technical education programs at the high school and college level, it also serves manufacturers and technology companies in Northern California with customized training & technical support; provides entrepreneurs with access to rapid prototyping and other manufacturing technologies. Clients benefit from training in Process Improvement, Lean Manufacturing, Concurrent Engineering, Rapid Prototyping, Solid Modeling, Supply Chain Management, IPC Solder & Wiring Workmanship Standards, Systematic Problem Solving, Technical Writing and Business Communication.

The work and services that Sierra College CACT currently provides is quite significant. There are however a few recommendations that can be made to further improve their operations, thereby providing more effective and influential services.

5.6.1 Marketing and Education

The growth and popularity of AM and the benefits that it can provide to various industries have definitely generated a lot more awareness in the public domain. And although there is this general growing awareness, there are however still a lot of companies that may not have an appreciation of how they in particular can benefit from this technology. Therefore a strong component of the CACT efforts to provide AM services to industry should continue to include targeted efforts at providing education through various public workshops, and marketing media (brochures, websites and other written media).

In particular, the CACT may consider an upgrade to their existing website with more media rich content, as well as functionality to provide online quotations for printing parts based on material selection and part volume.

The CACT is encouraged to continue to invest in long term industry partnerships – both with key role players from different industries, as well as AM machine and software developers. These partnerships will establish credibility and provide opportunities for marketing exposure through joint projects.

5.6.2 Improved Services

Depending on future strategies, the CACT may wish to consider automating their printing services to industry in a similar format that successful companies like Shapeways, i.Materialise, Autodesk 123D and Cubify have begun to do. These companies have placed a high emphasis on using online tools for users to either design/customize the parts for printing online or to upload their design files (created separately offline). Other services that the CACT can capitalize on more are the use of their 3D scanner to reverse engineer parts for companies. Being a desktop scanner, the NextEngine laser scanner has limited capabilities, but can nevertheless prove valuable to digitize smaller components.

5.6.3 Expanding New Areas of Application

The CACT's involvement with Sierra College gives it a unique opportunity to gain exposure to a very wide range of applications through the inclusion of all the different faculty programs discussed earlier. As these programs begin to experiment with different ways in which 3D printing can benefit their field of work, new applications will begin to emerge. Each of those faculty programs has their set of contacts to industry and in this way, the CACT will begin to gain further exposure to new industry partnerships through new applications.

Conclusions

Service providers have been around for more than 20 years and will likely continue for years to come due to the demand for the specialized additive manufacturing and secondary services they provide. Many companies have or will invest in low-cost 3D printers for concept modeling, but many will not have the volume of work or capital to justify larger, more expensive equipment. Also, service providers offer extensive experience and valuable advice and direction to their customers.

Clearly, a divergence has occurred among service providers, when comparing them from the past to today. Broadly, three different business models have developed. The first is one in which a service provider offers a broad array of technologies and services. They provide value to their customers in the form of capacity, choice, and broad expertise. A second business model is the company that has opted to concentrate on one or two AM technologies, mostly aimed at prototype and product development applications. The third model is one where various service providers have focused on becoming specialists in a certain technical area and have morphed their organizations toward being more of a manufacturing company, typically providing large OEMs with product-specific parts. Often this category of service provider will also concentrate in one or two industries such as aerospace, medical, or automotive.

As the industry matures, so will the companies that have been a vital part of it. As in most other industries, no single company will entirely dominate. Every service provider has an opportunity to provide a valuable service using the best methods, the latest technologies, and excellent customer service. As the awareness of additive manufacturing continues to increase within various companies and the public at large, many new opportunities for service providers will develop. In particular, service providers that have the resources and foresight to exploit their areas of expertise will have significant opportunity to expand over the coming years.

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Recommended for Further Reading

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Appendices

6 Appendix A: List of Consortia and Collaborations

Non-competitive collaboration has played an important role in the development of the AM industry. Types of collaboration include user groups, conferences and exhibitions, online forums, industry roadmaps, industrial consortia and government. Additional types are educational entities and working groups dedicated to establishing AM industry standards and educational curricula.

Workshops and road mapping events covering topics related to AM have helped guide industry and government organizations. One example is the 1998 Industrial Roadmap for the Rapid Prototyping Industry organized by the National Center for Manufacturing Sciences. Another is the 2009 Roadmap on Additive Manufacturing (RAM) and accompanying RAM workshop in Washington, D.C. In both instances, leaders in industry, academia, and government came together to create a shared vision of the future of additive manufacturing.

6.1 Additive Manufacturing Consortium (AMC)

The Additive Manufacturing Consortium (AMC) was established in 2010, with the first meeting in December of that year. As of May 2012, it consisted of 31 members and partners from industry, government, and academia from across the U.S. The formation of the AMC was inspired, in part, by the 2009 Roadmap for Additive Manufacturing (RAM), coupled with a groundswell of interest from industry, particularly by EWI in Columbus, Ohio. EWI is a national center for the advancement of joining and allied technology, which makes it a natural fit as coordinator of this national effort.

Industrial membership of AMC includes a supply chain of aerospace OEMs, equipment and consumable suppliers, service providers, and small and medium-sized enterprises in modeling and controls for AM. Five government agencies are involved to serve the needs of the major defense agencies and other branches of government. Several universities, national labs, and other organizations at the forefront of AM development are involved as invited partners. Based on this distributed national capability, with more than 50 AM machines and many key technical experts, the AMC represents a national test bed center as defined in the 2009 RAM. The current focus of AMC continues to be in the aerospace and defense industries. However, representatives of other industries are showing increased interest in the networking opportunities, benefits, and synergies for materials data and the other items related to the advancement of the manufacturing readiness of AM technologies.

6.2 National Network for Manufacturing Innovation (NNMI)

In March 2012, the U.S. White House announced new efforts to support manufacturing innovation. Central to the announcement is a proposed investment of $1 billion for a National Network for Manufacturing Innovation (NNMI). It would involve up to 15 institutes across the U.S., each serving as a regional hub of manufacturing excellence. They would be matched dollar for dollar by investment from non-government organizations. The NNMI is expected to bring together industry, universities, community colleges, federal agencies, and states to accelerate innovation. It hopes to:

1. Bridge the gap between basic research and product development,

2. Provide shared assets to help small manufacturers access to cutting-edge capabilities and equipment, and
3. Create an unparalleled environment to educate and train students and the workforce in advanced manufacturing skills.

The administration contends that this model has been successfully deployed in other countries and represents chance to fill a gap in U.S. manufacturing innovation.

The White House presented three broad areas of opportunities, one of which is 3D printing. The other two areas of opportunity cited in the announcement were the development of lightweight materials and the creation of a smart manufacturing infrastructure and approaches that make real-time use of “big data” flows to improve productivity and optimize supply chains. AM technology can also play a significant role in these two areas.

6.3 RapidTech and MatEd

The National Science Foundation funds two Advanced Technological Education (ATE) centers associated with additive manufacturing. The ATE program is an initiative aimed at two-year colleges. One of the two ATEs is the National Center for Rapid Technologies (RapidTech). It supports industry and education in the adoption of rapid technologies to increase global competitiveness. The center is part of Saddleback College (Mission Viejo, CA), but its staff and equipment are housed at the University of California-Irvine.

The other ATE is the National Resource Center for Materials Technician Education (MatEd), housed at Edmonds Community College (Lynnwood, Washington). MatEd and RapidTech have partnered to develop new AM core competencies and curriculum based on newly developed global ASTM industry standards.

RapidTech, MatEd, and their partner institutions are pioneering the development of educational and training programs focused on additive manufacturing technology. RapidTech offers courses in AM technology that feature hands-on experience with a broad range of AM processes. It also hosts an annual workshop that combines presentations with hands-on lab activities for college educators and administrators from across the U.S.

6.4 California Network for Manufacturing Innovation (CNMI)

In March 2013, the California Network for Manufacturing Innovation, Inc. (CNMI) was formally established as a non-profit corporation for the purpose of promoting manufacturing competitiveness in California through a collaboration of industry, national laboratories, technical assistance, government agencies, academia, workforce and economic development organizations. CNMI is designed to create a unified voice and plan to create programs and physical centers for California’s small and medium-sized manufacturers to have access and use advanced manufacturing technology to help them grow and compete in the global marketplace. The CNMI consortium has identified the following key activities [8]:

- Attract and enable delivery of manufacturing innovation in California
- Provide value to California manufacturers from Technology Developers to SMEs to Fortune 100 companies
- Reduce risks to companies in adopting new innovations in manufacturing

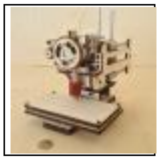
- Communicate and advocate the value of manufacturing innovation and manufacturers in California

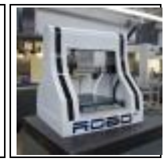
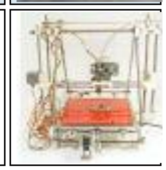
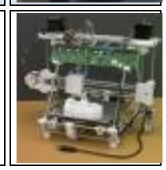
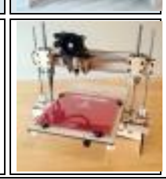
And furthermore, CNMI have identified the following strategic goals [8]:

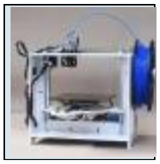
- Improve the transfer of technology to California manufacturers
- Engage other collaboratives to improve funding and resources directed at manufacturing innovation
- Develop industry partners to enhance workforce skills
- Combine research and development efforts of collaborators
- Conduct advocacy to enhance manufacturing environment in California

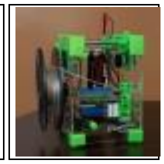
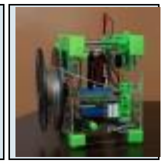
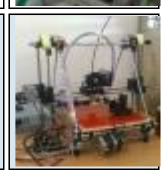
7 Appendix B: Price Comparison of Personal 3D Printers

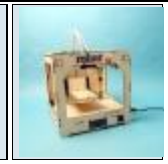
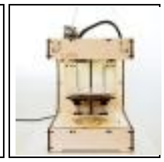
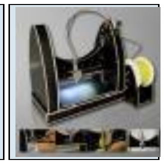
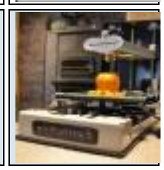
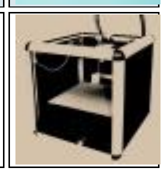
The following list of 3D printers has been included in this report for convenience sake, but has been compiled from information provided on the website of 3ders (www.3ders.org). An updated list can be viewed on their website [24].

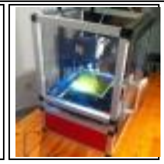
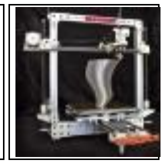
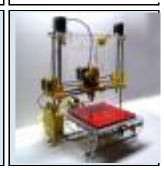
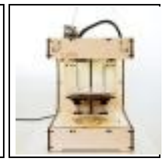
Nr.	Country	Manufacturer	Model	Assembled	Build envelope (W x D x H mm)	Image	Price (US$)	Lead time
1	USA	Printrbot	Printrbot Simple	DIY kit	-		$ 299.00	-
2	Singapore	Pirate 3D	Buccaneer 3D printer	Yes	150x100x120		$ 347.00	Dec. 2013
3	USA	Printrbot	Printrbot jr	DIY kit	114x140x102		$ 399.00	2-3 weeks
4	Canada	Mixshop	Prusa Mendel Full Kit (Excluding Printed Plastic Parts)	DIY kit	200x200x140		$ 439.00	In stock
5	UK	Sumpod	Sumpod Delta	Yes	180x180x200		$ 463.00	May 2013
6	Canada	Mixshop	Mix G1 Full Kit (Including all the parts)	DIY kit	170x150x170		$ 495.00	In stock
7	USA	Solidoodle	Solidoodle 3D Printer, 2nd Generation	Yes	152x152x152		$ 499.00	In stock
8	Singapore	Portabee	Portabee 3D printer kit (unassembled)	DIY kit	120x120x120		$ 499.00	3 weeks
9	USA	Invent Apart	RigidBot 3D printer	Yes	254x254x254		$ 499.00	-
10	USA	Printrbot	Assembled Printrbot jr	Yes	102x102x102		$ 499.00	2-3 week

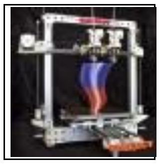
11	France	RepRap France - eMotion Tech	Prusa Mendel V2 complete kit excluding plastic parts	DIY kit	220x220		$ 544.98	-
12	USA	Printrbot	Printrbot LC	DIY kit	152x152x152		$ 549.00	3-4 week
13	USA	Robo 3D	RoBo 3D "PLA only" Non-Assembled DIY kit	DIY kit	254x254x203		$ 550.00	-
14	USA	Eventorbot	Eventorbot 3D printer	DIY kit	203x254x152		$ 580.00	-
15	Singapore	Romscraj	Durbie Prusa Mendel Reprap Complete Kit	DIY kit	200x200x140		$ 585.00	In stock
16	USA	Robo 3D	RoBo 3D "PLA Model" Fully Assembled	Yes	254x254x203		$ 599.00	-
17	UK	RepRapPro	Complete RepRapPro Huxley Kit	DIY kit	140x140x110		$ 621.00	-
18	France	RepRap France - eMotion Tech	Prusa Mendel V2 complete kit including plastic parts	DIY kit	220x220		$ 640.00	-
19	India	Makemendel	Orca v0.40 Kit with Linear Bearings (Unassembled)	DIY kit	220x220x165		$ 649.00	2-3 weeks
20	India	Makemendel	RapidBot 1.0 Kit	DIY kit	220x220x165		$ 649.00	In stock
21	USA	Printrbot	Printrbot PLUS	DIY kit	203x203x203		$ 699.00	3-4 week

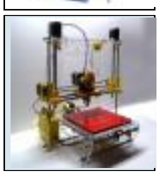
22	India	Makemendel	RapidBot 3.0 Kit	DIY kit	220x220x165		$ 699.00	In stock
23	India	Makemendel	Mendel Kit (Unassembled and Excluding printed plastic parts)	DIY kit	200x200x140		$ 699.00	out of stock
24	India	Makemendel	RapidBot 2.0 Kit	DIY kit	220x220x165		$ 749.00	2 days
25	Spain	3D Kits	3dkits F complet	Yes	400x520x370		$ 750.00	2 weeks
26	UK	RepRapPro	RepRapPro Mono Mendel	DIY kit	210x190x140		$ 773.00	-
27	USA	NW RepRap	Prusa Mendel Iteration 2 Complete Kit	DIY kit	-		$ 799.00	-
28	USA	Ultra-Bot	Ultra-Bot 3D printer	DIY kit	127x165x191		$ 799.00	-
29	USA	Solidoodle	Solidoodle 3D Printer, 3nd Generation	Yes	203x203x203		$ 799.00	In stock
30	USA	Makergear	Prusa Mendel	DIY kit	203x203x203		$ 799.00	2 weeks
31	Korea	Backho (White Tiger) company	Willybot 1.3	DIY kit	-		$ 800.00	7 days
32	USA	Deezmaker	Bukobot Mini "Green"	DIY kit	125x125x125		$ 850.00	In stock

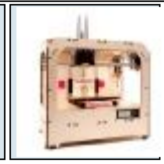
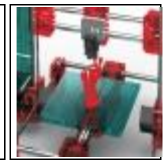
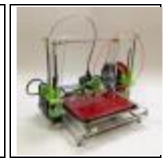
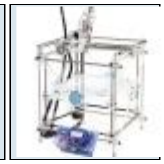
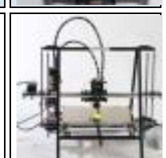
33	China	PP3DP	UP! mini	Yes	120x120x120		$ 899.00	7 days
34	USA	Invent Apart	RigidBot Big 3D printer	Yes	300x400x254		$ 899.00	-
35	USA	Tantillus	Tantillus 3D printer	DIY kit	100x100x100		$ 925.00	2-4 weeks
36	USA	Tantillus	Tantillus 3D printer	Yes	100x100x100		$ 925.00	-
37	Germany	German RepRap Foundation	GRRF PRotos Complete Kit RR-KIT-PR1	DIY kit	225x225x140		$ 934.00	in stock
38	Italy	Store Open Electronics	3Drag 3D printer	DIY kit	200x200x200		$ 938.00	-
39	Singapore	Portabee	Panther 3D Printer	Yes	202x162x157		$ 960.00	4 weeks
40	Italy	Ac123Dc	Mendel Prusa kit without plastic parts	DIY kit	200x200x200		$ 986.00	1-2 days
41	Taiwan	Intelligent Machine Inc.	Metalbot Metal RepRap compatible 3D printer	Yes	195x195x160		$ 990.00	-
42	Italy	Sharebot	ShareBot K 3D Printer Kit	DIY kit	200x 200 x200		$ 991.00	-
43	USA	QU-BD	Revolution XL 3D printer	Yes	228x216x228		$ 999.00	6-8 Weeks

44	China	Mbot 3D	Mbot Cube Single head	Yes	200x200x200		$ 999.00	2-4 weeks
45	Canada	Tinkerine Studio	Litto 3D printer	DIY kit	135x120x175		$ 999.00	4-6 weeks
46	Italy	CSP	POWERWASP	Yes	260x200x210		$ 1,000.00	4 weeks Italy / 6 weeks elsewhere
47	USA	SeeMeCNC	Rostock MAX Complete 3D Printer Kit	DIY kit	279x279x349		$ 1,000.00	7-10 days
48	Finland	miniFactory	miniFactory 3D printer	Yes	140x150x140		$ 1,010.00	3~5 days
49	Netherlands	Mendel Parts	Orca v0.43 Unassembled	DIY kit	250x220x190		$ 1,067.00	2-3 weeks
50	China	Mbot 3D	Mbot Cube double head	Yes	200x200x200		$ 1,099.00	14 days
51	UK	Sumpod	Sumpod Aluminium	Yes	240x240x150		$ 1,099.00	4 week
52	Netherlands	Felix Printers	Felix 1.0 Complete Kit	DIY kit	260x200x200		$ 1,115.00	2-4 weeks
53	UK	RepRapPro	RepRapPro Tricolour Mendel	DIY kit	210x190x140		$ 1,129.00	-
54	South Korea	BatBot	BatBot 3D printer	DIY kit	180x180x210		$ 1,166.00	-

55	Germany	iRapid	iRapid Compact V2	Yes	100x100x100		$ 1,173.00	-
56	Italy	Ac123Dc	Mendel Prusa full kit with assembled electronics LM8uu	DIY kit	200x200x200		$ 1,196.00	2-3 days
57	USA	Deezmaker	Bukobot 8 Vanilla 3D Printer kit	DIY kit	200x200x200		$ 1,199.00	In stock
58	Canada	Tinkerine Studio	Ditto Plus 3D printer	DIY kit	210x185x230		$ 1,249.00	4-6 weeks
59	India	Makemendel	RapidBot Mega	DIY kit	750x250x200		$ 1,250.00	3-4 Weeks
60	USA	Airwolf 3D	AW3D V.5	DIY kit	200x200x150		$ 1,295.00	5 days
61	Canada	Tinkerine Studio	Litto 3D printer Assembled	Yes	135x120x175		$ 1,299.00	4-6 weeks
62	Germany	ReprapSource	Shapercube 2.1	DIY kit	190x190x180		$ 1,302.00	3-4 weeks
63	UK	Bits from Bytes	RapMan 3.2 3D Printer Kit Extreme (NBHE)	DIY kit	270x205x210		$ 1,376.00	2 weeks
64	USA	Hyrel 3D	Hyrel 3D printer	Yes	200x200x200		$ 1,395.00	-
65	USA	Type A Machines	Series 1	Yes	230x230x230		$ 1,400.00	4-6 weeks

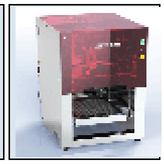
66	China	Weistek	WT2 3D printer	Yes	150x150x130		$ 1,415.00	-
67	USA	Makergear	M2	DIY kit	203x254x203		$ 1,450.00	6 weeks
68	USA	MendelMax	MendelMax 2.0 Beta Kit	DIY kit	245x315x225		$ 1,495.00	4 weeks
69	USA	Deezmaker	Bukobot 8 Duo (Dual Extruder)	DIY kit	200x200x200		$ 1,495.00	In stock
70	China	PP3DP	UP! Plus	Yes	140x140x135		$ 1,499.00	3-5 days
71	USA	Afinia	Afinia H-Series	Yes	140x140x135		$ 1,499.00	-
72	USA	Printrbot	Printrbot GO	DIY kit	200x185x150		$ 1,499.00	In stock
73	USA	Tantillus	Tantillus 3D printer	Yes	100x100x100		$ 1,500.00	2-4 weeks
74	Canada	Tinkerine Studio	Ditto Plus 3D printer Assembled	Yes	210x185x230		$ 1,549.00	4-6 weeks
75	USA	Cubify	Cube 3D printer	Yes	140x140x140		$ 1,569.00	-
76	UK	Bits from Bytes	RapMan 3.2 3D Printer Kit Universal (BHE-NS)	DIY kit	270x205x210		$ 1,589.00	2 weeks

77	Netherlands	Code-p	Builder	Yes	220x220X175		$ 1,597.00	10-15 days
78	Netherlands	Ultimaker	Complete Ultimaker Kit	DIY kit	210x210x220		$ 1,598.00	In stock
79	UK	A1 Technologies	Maxit	DIY kit	210x160x100		$ 1,610.00	-
80	UK	York 3D Printers	Buildabot 'Revolution' 3d Printer Kit	DIY kit	210x210x160		$ 1,624.00	3-5 weeks
81	South Korea	BatBot	BatBot 3D printer	Yes	180x180x210		$ 1,632.00	-
82	Japan	Hot Proceed	Blade-1	Yes	100x100x100		$ 1,642.00	-
83	USA	Hyrel 3D	HYREL Engine with dual extruders	Yes	150x150x200		$ 1,645.00	-
84	Netherlands	Leapfrog	Creatr	Yes	300x250x260		$ 1,669.00	-
85	France	Multistation	Extru3D V2	DIY kit	275x205x210		$ 1,684.00	-
86	USA	Airwolf 3D	AW3D V.5 Assembled	Yes	200x200x150		$ 1,695.00	24 hours
87	USA	Lulzbot	AO-101 3D Printer	Yes	200x190x100		$ 1,725.00	In stock

88	USA	Makerbot	Replicator Single	Yes	225x145x150		$ 1,749.00	out of stock
89	Germany	Fabbster	Fabbster kit	DIY kit	230x230x210		$ 1,800.00	N/A
90	Brazil	Metamáquina	Metamáquina 2	DIY kit	200x200x150		$ 1,876.00	-
91	USA	Airwolf 3D	AW3D XL	DIY kit	300x200x178		$ 1,895.00	10 days
92	UK	Bits from Bytes	RapMan 3.2 3D Printer Kit Ultimate (DH-NS)	DIY kit	270x205x210		$ 1,937.00	2 weeks
93	USA	Hyrel 3D	HYREL BIG Engine with single extruder	Yes	200x200x200		$ 1,995.00	-
94	Poland	CB-Printer	3D Printer CB-printer KIT	DIY kit	200x200x180		$ 2,031.00	-
95	USA	The Future is 3-D	12"d x 12"w x 10"h with Heated Build Platform Glacier Steel	Yes	305x305x241		$ 2,100.00	8~10 weeks
96	UK	Bits from Bytes	RapMan 3.2 3D Printer Kit Education	DIY kit	270x205x210		$ 2,166.00	2 weeks
97	USA	TrinityLabs	Aluminatus TrinityOne 3d Printer	Yes	300x300x300		$ 2,199.00	-
98	USA	Makerbot	Replicator 2	Yes	285x153x155		$ 2,199.00	6 weeks

99	USA	Hyrel 3D	HYREL BIG Engine with dual extruders	Yes	200x200x200		$ 2,245.00	-
100	UK	York 3D Printers	Buildabot 'Revolution' 3d Printer - Fully Built	Yes	210x210x160		$ 2,275.00	3-5 weeks
101	Poland	CB-Printer	3D Printer CB-printer.com	Yes	200x200x180		$ 2,294.00	-
102	USA	Airwolf 3D	AW3D XL Assembled	Yes	300x200x178		$ 2,295.00	10 days
103	Taiwan	Rays Opitcs	MiiCraft 3D printer	Yes	43x27x180		$ 2,299.00	4-8 weeks
104	Netherlands	MaukCC	CartesioM V0.7	DIY kit	200x200x200		$ 2,343.00	2-3 weeks
105	Netherlands	MaukCC	CartesioLD V0.6	DIY kit	200x400x200		$ 2,351.00	3-4 weeks
106	USA	Essential Dynamics	Imagine 3D Printer	Yes	229x229		$ 2,799.00	-
107	France	Multistation	Extru3D V2 Assembled	Yes	275x205x210		$ 2,882.05	-
108	USA	B9Creations	B9Creator 3D printer KIT	DIY kit	77x102x203		$ 2,990.00	-
109	USA	Fablicator	Fablicator	Yes	178x178x178		$ 3,000.00	-

110	UK	Sumpod	Sumpod Mega	Yes	600x600x600		$ 3,018.00	4 weeks
111	USA	Formlabs	The Form 1 3D printer	Yes	125x125x165		$ 3,299.00	May 2013
112	Netherlands	PP3DP	UP! Plus	Yes	140x140x135		$ 3,341.00	-
113	UK	Bits from Bytes	3DTouch™ 3D Printer (Single Head)	Yes	275x275x210		$ 3,458.00	3 weeks
114	USA	Hyrel 3D	HYREL SYSTEM with dual extruders	Yes	200x200x200		$ 3,500.00	-
115	USA	The Future is 3-D	16"d x 16"w x 21"h with Heated Build Platform Glacier Peak	Yes	406x406x445		$ 3,650.00	-
116	UK	Bits from Bytes	3DTouch™ 3D Printer (Double Head)	Yes	230x275x210		$ 3,899.00	3 weeks
117	Italy	Robot Factory	3D-One	Yes	245x245x245		$ 3,957.00	-
118	Taiwan	EZ 3D printers	EZ 3D Printer-200	Yes	200x150x100		$ 3,985.00	-
119	Cyrus	Open Source Romote Control	Ilios HD SLA 3D Printer Kit	DIY kit	300x300x200		$ 4,183.00	-
120	UK	Bits from Bytes	3DTouch™ 3D Printer (Triple Head)	Yes	185x275x210		$ 4,326.00	3 weeks

121	Taiwan	EZ 3D printers	EZ 3D Printer-200H	Yes	200x150x150		$ 4,495.00	-
122	China	Zbot.cc	Zbot	Yes	250x250x200		$ 4,500.00	-
123	USA	B9Creations	B9Creator 3D printer	Yes	77x102x203		$ 4,995.00	-
124	Germany	Kühling&Kühling	RepRap Industrial 3D printer	DIY kit	200x200x200		$ 5,412.00	October 2013
125	USA	Asiga	Freeform Pico	Yes	40x30x75		$ 6,990.00	-
126	Netherlands	Leapfrog	Xeed	Yes	370x340x290		$ 7,290.00	-
127	Italy	Robot Factory	3DLPrinter	Yes	102x78x160		$ 7,833.00	-
128	USA	Asiga	Freeform Pico Plus27	Yes	35x21.8x75		$ 8,990.00	-
129	USA	Asiga	Freeform Pico Plus33	Yes	42.5x26.5x75		$ 8,990.00	-
130	USA	Asiga	Freeform Pico Plus39	Yes	50x31.2x75		$ 8,990.00	-
131	USA	Solido	Solido SD300 Pro 3D Printer	Yes	160x210x135		$ 9,995.00	-

132	Denmark	Blue Printer	SHS 3D Printer	Yes	160x200x140		$ 13,186.00	-
133	Germany	envisionTEC	Perfactory Micro	Yes	40x30x100		$ 16,520.00	-
134	USA	Solidscape	3Z Studio	Yes	152x152x51		$ 24,650.00	-

Author's Biography

Dr. Neal de Beer

With more than 10 years of experience in the field of Additive Manufacturing (AM), Dr. de Beer has devoted his research efforts towards characterizing 3D-Printing capabilities and more recently to the applications of AM for the medical field. He obtained his MSc and PhD degrees in Industrial Engineering in 2004 and 2011 respectively from the University of Stellenbosch, South Africa. Dr. de Beer has worked as research coordinator at the Laboratory for Rapid Product Development at Stellenbosch University, where he guided numerous under- and postgraduates with their research projects. In 2009 and 2012, Dr de Beer served as committee member for the Rapid Product Development Association of South Africa. During 2012, he completed a postdoctoral fellowship at Stellenbosch University where he initiated the Biofabrication Research Group. In 2013, he immigrated to the United States with his wife and son and is currently working as a consultant for the Center for Applied Competitive Technologies (CACT) at Sierra College, Rocklin CA. His specific areas of interest include the use of Additive Manufacturing for design innovation, particularly in the areas of patient-specific implants, prosthetics and surgical guides. He has published 37 articles and conference proceedings, and has served as reviewer for both the Rapid Prototyping Journal and the South African Journal of Industrial Engineering.