Chapter 2
Industries and Applications

This chapter provides details of AM application sectors. It starts with the status of the technology in the global economic market and goes on to discuss three leading application sectors, namely the healthcare, automotive and aerospace industries as well as applications relating to consumer goods. Empirical evidence and the status of AM implementation in these industries is thoroughly described. It also outlines the main advantages to each industry of adopting AM technologies. The chapter discusses other application sectors as well, including building and architecture, food, and pharmaceutical industries along with applications for education and research institutes.

2.1 The Role of Additive Manufacturing in the Industry of the Future

The world has already seen three industrial revolutions in its history. The first dates back to the late eighteenth century and coincided with the introduction of the steam engine. The second is historically allocated to the last thirty years of the nineteenth century, with the advent of electricity that allowed the first mass production, and the third, since 1970, with the massive use of information and communication technology in plants. The so-called fourth industrial revolution, or Industry 4.0, is still underway. The term "Industry 4.0" was coined in Germany at the prestigious Hannover Industrial Fair in 2011. Since then, both national governments and private companies have launched numerous initiatives to develop this new manufacturing paradigm.

Policymakers, practitioners and scholars agree that Industry 4.0 is a new manufacturing paradigm triggered by new disruptive technologies. Baur and Wee (2015) reported for McKinsey on the four disruptions that are driving Industry 4.0: (1) the astonishing rise in data volumes, computational power, and connectivity,

M. Khorram Niaki and F. Nonino, *The Management of Additive Manufacturing*,
Springer Series in Advanced Manufacturing,
https://doi.org/10.1007/978-3-319-56309-1_2

(2) the emergence of analytics and business-intelligence capabilities, (3) new forms of human-machine interaction and (4) improvements in transferring digital instructions to the physical world. The fourth clearly relates to 3D printing and additive manufacturing technologies. In March 2015, the World Economic Forum's Global Agenda Council on the Future of Software and Society launched a survey aimed at identifying megatrends and technological tipping points—moments when specific technological shifts hit mainstream society. The report produced in September 2015 proposed six megatrends:

1. People and the internet
2. Computing, communications and storage
3. The internet of things
4. Artificial intelligence (AI) and big data
5. The sharing economy and distributed trust
6. The digitization of matter

The sixth megatrend refers to physical objects "printed" from raw materials via additive, or 3D printing. Moreover, the report proposes twenty-one tipping points in a resulting timeline ranging from 2018 to 2027 (Fig. 2.1).

Among the resulting overview of the expectations, the report contains the following tipping points in 2025 related to AM technologies:

- The first 3D-printed car in production (84.1% of agreement)
- 5% of consumer products printed in 3D (81.1%)
- The first transplant of a 3D-printed liver (76.4%)

During more than two decades of commercializing AM technology, the compound annual growth rate (CAGR) of worldwide revenues of all AM products and services was 25.4% in 2013. The growth rate increased by 27.4% over the three-year-period of 2010–2012, reaching $2.2 billion in 2012. The number of AM systems sold (unit price > $5000) increased by 19.3% to 7771 in 2012, while the unit sales of 3D personal printers (unit price $\leq$ $5000) increased by 46.3% to

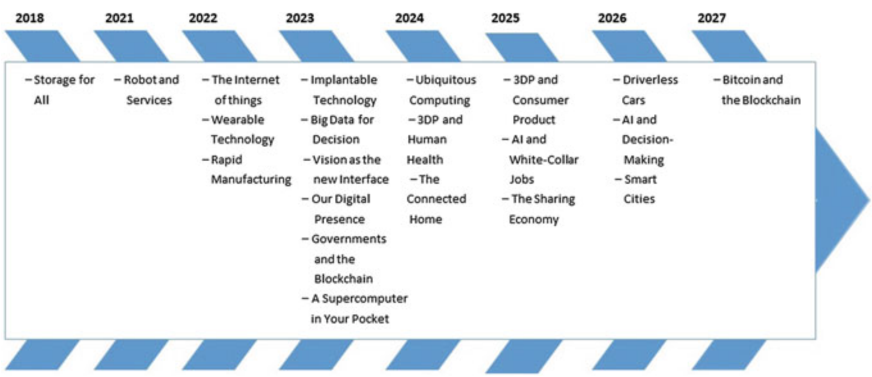


Fig. 2.1 Timeline of the twenty-one tipping points that will change industry and society. *Source* (Based on the survey conducted by World Economic Forum 2015)

35,508 in the same year. It demonstrates the spread of the technology for low-price 3DP among the retailers and end consumers. The AM market also continued its increasing growth in 2014. The market for AM, involving all AM products and services worldwide, grew at a CAGR of 35.2% to $4.1 billion in 2014, according to Wohlers and Caffrey (2015). The industry expanded by more than $1 billion in 2014, with forty-nine manufacturers producing and selling industrial-grade AM machines. The CAGR over the past three years (2012–2014) was 33.8%.

According to Wohlers' research, the global AM industry is expected to grow from $3.07 billion in revenue in 2013 to $12.8 billion by 2018, and exceed $21 billion in worldwide revenue by 2020. Siemens also predicted that 3D Printing would be a €7.7 billion ($8.3B) global market by 2023. Forecasting the market trends of future years has been difficult, considering the progressive growth during the recent period. Manyika et al. (2013) from the McKinsey Global Institute reported further adventurous predictions, estimating that AM could generate an economic impact of $230 billion to $550 billion per year by 2025, based on reducing costs and the value of customization; the largest source of potential impact would be from consumer uses.

SmarTech Publishing is one of the leading industry analysts in the AM environment, producing many reports per year pinpointing the major opportunities in the sector. The institution expects for 2017, that the dental and medical application sectors will drive a significant portion of the industry's market growth. In the healthcare industry, AM is becoming a viable and accepted technology, with a growing presence particularly in the surgical sphere (e.g., cardiac and orthopedic uses).

2.2 Industrial Diffusion

Researchers are currently demonstrating the rapid spread of AM technologies, and according to the results of the survey of more than 100 industrial manufacturers made by PwC (PricewaterhouseCoopers) Technology Forecast, approximately 67% of manufacturers are already using 3D printing (Fig. 2.2). Of these, 28.9% are experimenting to determine how 3D printing can be integrated into their current production, and 24.6% are using 3D printing for prototyping.

Another piece of research investigated the reasons for pursuing AM technologies. In 2014, Gartner, Inc. conducted a worldwide survey, involving 330 individuals. The participants were employees of organizations with at least 100 employees that are using or planning to use AM technologies (Fig. 2.3). The results show more than half were already using AM in the initial stage of manufacturing, aimed at the product development process. An interesting finding of this research is that 60% of the respondents said that high start-up costs are a main reason for delays in implementing the technology. However, most of the early adopters found clear benefits in different aspects while adopting AM technologies. It shows that more and more organizations will be attracted to use 3D printing as technical

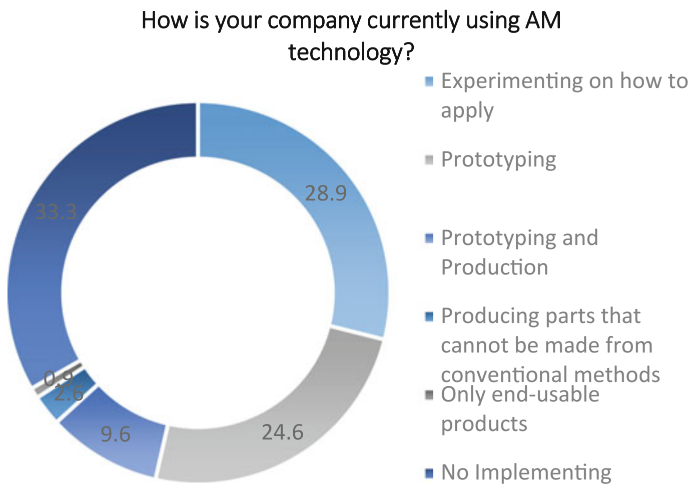


Fig. 2.2 A survey on the AM industrial diffusion level, 2014 (Based on the data of PwC)

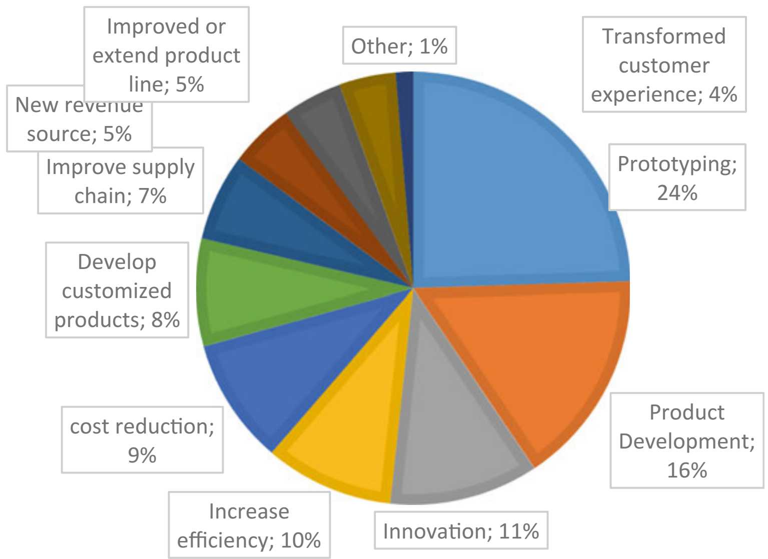


Fig. 2.3 Reasons for pursuing AM technology, 2014 (Based on the data from Gartner, Inc)

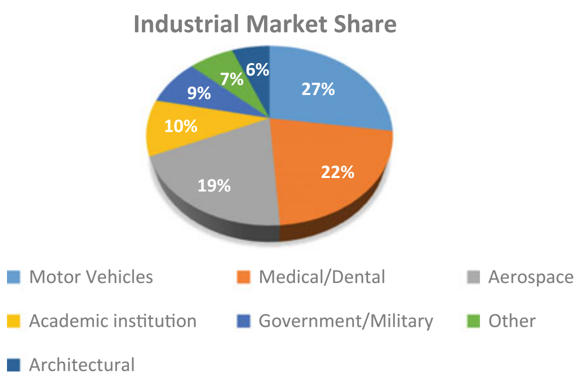
improvements are made and start-up costs reduce, According to the PwC estimation, 67% of the manufacturers already use AM technology, and given technological improvement in recent years, we can estimate a greater adoption rate among manufacturers in the near future. Considering all the target communities, involving consumers, industries and life science, Gartner also predicts almost 50% of them will adopt AM technology—by the year 2018—in their services and in the production of parts for the items they consume and sell.

Furthermore, a SmarTech market publication in May 2014 investigated and predicted the AM market in detail. The total AM market is divided into four sections, constituting software, services, material, and equipment, which respectively contributed 5, 23, 26, and 46% of the AM market share in 2013. In addition, it predicts that by 2023, the AM market share for each will be respectively 10, 14, 28, and 48%. It shows also the necessity of focusing on software and material development to produce a more powerful and more widespread manufacturing technology. Another interesting analysis was performed in order to distinguish the industrial sectors inside AM markets. For instance, the automotive industry's adoption of 3D printing is projected to increase from $365.4 million in 2015 to $1.8 billion in 2023, making a 19.51% CAGR. The aerospace industry's adoption of 3D printing solutions is projected to increase from $723 million in 2015 to $3.45 billion in 2023, a CAGR of 18.97%.

Wohlers (2012) reports the share of each application sector (Fig. 2.4). Automotive, aerospace, medical, consumer products, and other industrial parts have respective shares of 17.3, 12.3, 13.7, 18.5, and 18%. The detailed discussion of these industrial sectors will be presented in Sect. 2.3.

Gartner et al. (2015) conducted a survey of 409 AM adopters among different industries and application sectors. The respondents were asked to answer regarding the level of impact of AM technology on the industry. Figure 2.5 illustrates the list of application sectors and their answers ranging from "AM is expected to have a strong hindering effect," to 'AM is expected to have a strong fostering effect," (on your industry) within the next ten years. The results demonstrate that some application sectors are more optimistic about the future of AM rather than others. These application sectors, of which more than 80% perceived the fostering effects of AM, include consumer goods (i.e., hobbies and models, arts and fashions), the automotive, aerospace, and healthcare industries among others, and research institutions.

Fig. 2.4 AM industrial market share



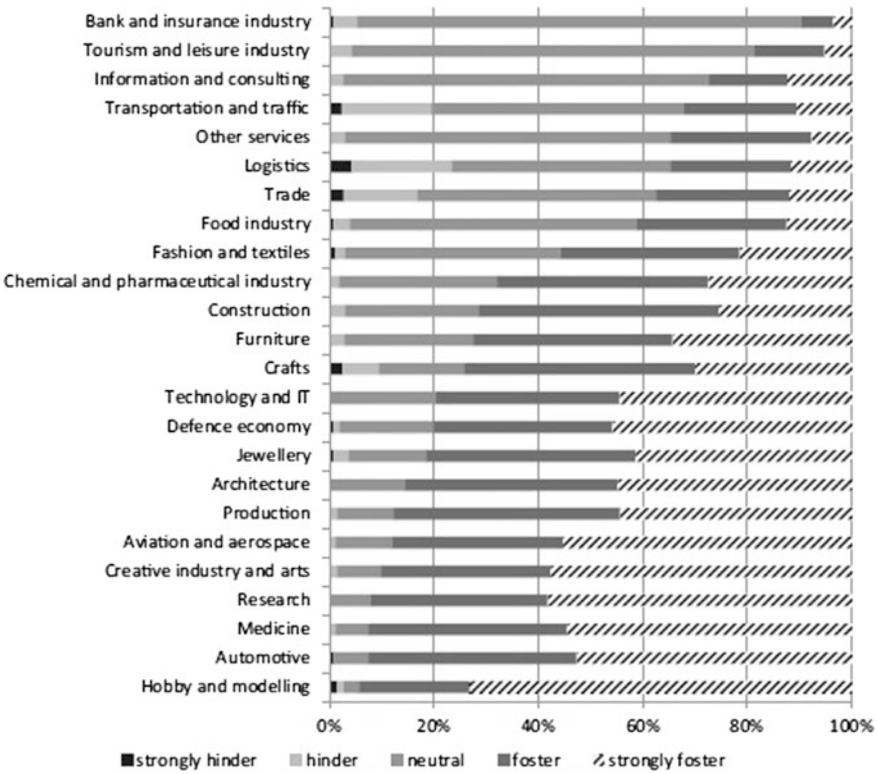


Fig. 2.5 Ten-year forecast of the impact of AM by Industry (n = 407). *Source* Gartner et al. (2015)

2.3 Main Application Sectors

2.3.1 Healthcare Industry

Medical products are one of the leading AM application sectors because medical products usually require a customized shape and functionality. As reported, nearly 15.1% of the U.S. AM market takes place within this industry, with AM shipments estimated to be $37.2 million, less than 0.05% of medical and dental manufacturing, and it also includes 16.4% of worldwide AM markets in 2013 (Wohlers 2014). AM has also been employed worldwide in the creation of around 30,000 prosthetic limbs, more than 500,000 dental implants, and numerous other devices (Campbell et al. 2012).

Since AM allows for fast and economic production of customized designs, it is well matched to applications in this sector. For instance, the ability to produce custom implants eliminates the need for time-consuming adjustments during surgery and reduces operating costs as well as the risk of medical complications

(Bogue 2013). In addition, the flexibility provided by AM allows surgeons to decide on the most proper part for each patient, and to simply modify and optimize the design, resulting in the improved performance of implants.

Giannatsis and Dedoussis (2009) classified the applications of AM in the medical sector as follows:

- Bio modeling, involving the fabrication of physical models of parts of the human anatomy and biological structures in general, for surgery planning or testing
- Design and fabrication of customized implants for prosthetic operations, rehabilitation, and plastic surgery
- Fabrication of porous implants (scaffolds) and tissue engineering
- Fabrication of specific surgical aids and tools
- Drug delivery and micron-scale medical devices

The use of AM in bio modeling for the purpose of surgery planning or for diagnostic uses was probably the first medical AM application (Gibson et al. 2010). Fabricating a model, which allows surgeons to see from any angle and can touch is very valuable. They use these custom-made models to identify complex surgical procedures. These models are usually first imaged by 3D imaging machines such as CT (computerized tomography—used to generate cross-sectional images, of the bones, blood vessels and soft tissues inside the body) or MRI (Magnetic Resonance Imaging, which uses radio waves to create an image of the organs), and are then transferred to the AM machine. Surgeons stated that having a multicolored, complex model of the head or abdominal area were priceless in planning surgeries, a process which can take 12–24 h and involve teams of surgeons and support staff. Digital personalized surgery (Fig. 2.6) is a workflow guiding the whole process from the medical imaging of the patient through to the surgery, transitioning from the virtual world to the physical world using perceptual design tools and software, surgical simulation and 3D printed surgical guides and models.

AM has found applications in a variety of surgeries such as pelvic surgery, neurosurgery, spinal surgery, cardiovascular surgery, and visceral surgery, while research demonstrates a significant improvement in diagnosis and treatment thanks to better 3D models of pathological structure, increased accuracy and the possibility

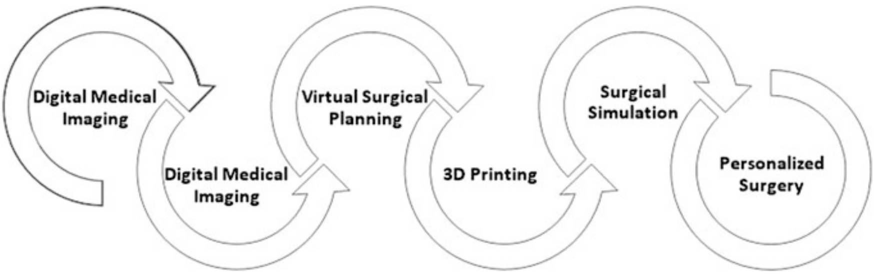


Fig. 2.6 Workflow of digital and personalized surgical planning

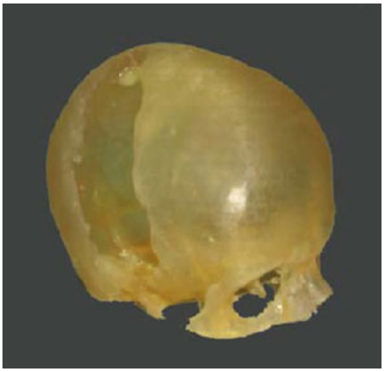


Fig. 2.7 A skull biomodel made by SLA. *Image Source* Giannatsis and Dedoussis (2009)

of pre-planning (Rengier et al. 2010). An example of a skull model, made by SLA, is presented in Fig. 2.7. This biomodel is an accurate replicate of the damaged skull of a young girl, which was used for pre-operative planning of the surgery and an aid for the design of the prosthetic implant. The first application phase included the use of AM for rapid tooling (RT) purposes. Then through the improvement of the technology and corresponding quality matters, AM technologies are employed in a variety of end-use parts rather than in models.

Manufacturers offer various devices and components for electrotherapy. For instance, one of the companies (Ivivi Technologies) uses AM technology in its product development process, yielding a positive return on investment in less than one year. The company argues that AM empowers designers to make product changes overnight. Therefore, AM is an amazing manufacturing method, in which manufacturers can modify products to meet their customers' needs in only a few hours, resulting in a boost to their customer relationships. In addition, AM gives the company a rapid and cost effective way of manufacturing customized medical parts, mostly by eliminating the need for tools.

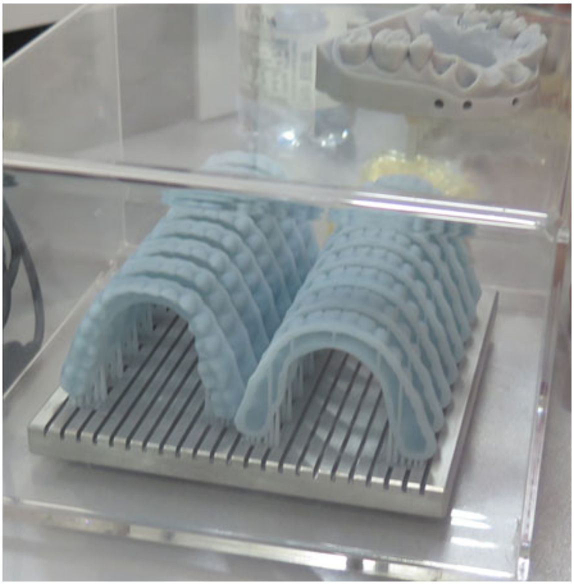
AM is also well suited to the production of prosthetics due to its ability to produce low volumes, complex designs, and customized parts. Although standard-sized implants are commercially available, these might not be usable in all cases. Rengier et al. (2010) argued the need for customized implants as follows: "(1) patients outside the standard range with respect to implant size- or disease-specific special requirements, (2) improved surgical outcome because of individual fitting and adequate match with individual anatomical needs". The series production of end-use parts has been applied in the fabrication of acetabular cups used as a hip joint replacement, produced using the Arcam EBM system. The use of AM allows the incorporation of embedded porosity to promote cell ingress.

AM has been also used in series production of dental parts. Vandenbroucke and Kruth (2007) state that "Dental applications are very suitable to be produced by SLM due to their complex geometry, strong individualization and high-aggregate price. Moreover, the manufacturing of multiple unique parts in a single production run could enable mass customization". 3D printing is finding growing applications in producing customized crowns, implants and bridges. A successful application of

RM is in orthodontic treatment, which involves the patient wearing a sequential series of customized clear plastic aligners. Each aligner in the series is produced indirectly from individual SL models. The adoption of AM in dental industries has an increasing number of advantages. For instance, NimroDENTAL Orthodontic Solutions is a service supplier to dentists in the London area. The company produced accurate functional models for aligners, crowns, and bridges more rapidly than with any previous method, using transparent and colored AM raw materials. In addition, the higher contrast of parts made using available materials compared to the traditional plaster models, results in better customer relationships (see Fig. 2.8). These models enable the patients to easily see how the orthodontic device looks and works. According to the experience of the company, better communication with patients as a result of the use of 3D printed models had a real and positive impact on customer satisfaction. They can 3D print up to twenty high-quality dental models on demand at short notice, saving time, lowering costs and reducing the need to store large numbers of physical models in the clinic. Furthermore, considering the nature of clinical areas, the size of 3DP and the cleanliness of production make it more effective than plaster model making.

AM has also found an application in the hearing aid industry (Fig. 2.9). For instance, Siemens and Phonak are both using AM systems for the series production of customized hearing aids. Two systems are currently available for the fabrication of customized hearing aids, SLS and SL (Hopkinson et al. 2006). AM technology is also being used routinely for the manufacture of plastic hearing aid parts, ranging from individual ear molds to shells with integrated faceplates. The success of AM in the hearing aid industry has been a particularly impressive example of how companies can take advantage of the shape complexity capability of AM technologies to

Fig. 2.8 Sample dental molds made by 3DP



economically achieve mass customization (Gibson et al. 2010). The AM replacement offers an almost fully automated solution, with a lead time down to a day and a "first-fit" rate of 95% (Ruffo and Hague 2007). According to Dr. Phil Reeves, reported in *3D Printing Industry* in 2013, "there are more than 10,000,000 3D printed hearing aids in use worldwide". Jenna Franklin, marketing associate of EnvisionTEC, a leading manufacturer of 3D printers, claims that the majority of existing hearing aids in the world are fabricated using 3D printers.

In recent years, scientists have developed a means of using a patient's cells to enable bioprinting of skin tissues and a range of other human body parts. Bioprinting involves placing living cells into just the right location with an AM machine, to fabricate functional, heterogeneous living tissue. In February 2013, experts from Weill Cornell Medical College used AM and injectable gels made of live cells to build a facsimile of a human ear (PrototypeToday 2013). According to a medical expert, "the ability to manufacture living human tissue for medical research and clinical practice has the potential to reshape the future of medicine" (IndustryWeek 2013). One of the major advantages of using AM in bioprinting with injectable gels, is a printer's ability to carefully squirt cells into precise patterns and shapes. In addition, the ability of AM machines to simultaneously print in multi-materials, means that biological researchers are a step closer to creating artificial tissue that mimics nature's complicated shapes, internal structures, and cellular diversity (Lipson and Kurman 2013).

Furthermore, in recent years a range of materials has been introduced. There are three types of polymers, used in the medical sector. These are biocompatible polymers for external use, biocompatible polymers for implants, and biodegradable polymers, also for implants (Petrovic et al. 2011). Biocompatible polymers for

Fig. 2.9 A hearing aid made by 3DP. *Image Source* Gibson et al. (2010)

external use involve those that can be used for medical or prosthetic devices. For instance, the e-shell 200 series material has been developed particularly for use in hearing aid products, because of its rigidity and durability. Other biocompatible polymers involve those that can be used in surgical implants. These materials do not result in rejection by the human body. An example of this group is the photopolymer R 11, used in the fabrication of coronary bypass implants. Hard tissue lumbar implants made with SLA for vertebral fixation have also been implanted (Goffin et al. 2001). In addition, several research studies have been conducted in order to obtain scaffolds for tissue engineering using polylactic glycolic acid (PLGA) and fibrin gel (Liu et al. 2009), or a combination of ether, epoxy resin and a photo initiator (Quadrani et al. 2005). Biodegradable polymers can be used in implants with the special feature of an osteoinductive function that allows bone growth and degrades over time. In addition, the flexible form of these polymers permits tissue engineering, as they can be used as a basic material for fabricating human organs (Petrovic et al. 2011). On the other hand, metal implants interface with living bone and tissue, with EBM and DMLS technologies both now used in the production of standard and customized implants. For instance, metals like titanium are used particularly in load-bearing areas, for instance in hip reconstruction (Rengier et al. 2010). Biocompatible materials include bioceramics such as hydroxyapatite which is currently the preferred material for bone reconstruction (Stevens et al. 2008). Commonly used biomedical materials for use in medical components are listed in Table 2.1. Moreover, several AM systems have been adopted in medicine including EBM, FDM, SLA, SLS, and DMLS.

In general, the emergence of AM in the medical sector provides a number of advantages. One of the most important of these is that the need to fabricate complex or customized designs in either single units or small volumes is already provided by AM. In addition, the product development process will be faster than with any conventional manufacturing method. When using AM in the medical sector, we usually start with a CT scan of the required zone, which is then transferred to an AM machine to be prepared. In addition, AM is able to fabricate gradual structures enabling production of lightweight parts, along with osteoinduction and osteointegration in implant manufacturing.

2.3.2 Automotive Industry

AM technologies have been employed in the automotive industry for a decade in prototyping, tooling and the production of special and customized parts in small volumes. AM shipments for the U.S. automotive industry were worth $48 billion in 2011. As mentioned above, approximately 19.5% of worldwide AM occurred within the automotive industry in 2012, with AM shipments estimated to be less than 0.05% of total U.S. automotive shipments (Wohlers 2012).

Due to the significant advantage provided by AM in the production of customized and small volume parts, RM applications were well established in

Table 2.1 Available biomedical materials and applications

Implant material	Abbreviation/notation	Application
Ti and Ti alloys	CP–Ti	Bone fixation
	Ti–6A1–4 V	Artificial valve, stent, bone fixation
	Ti–6Al–7Nb	Dental application, knee joint, hip joint
	Ti–5Al–2.5Fe	Spinal implant
	Ti–15 Zr–4Nb–2Ta–0.2Pd	Dental applications
	Ti–29Nb–13Ta–4.6Zr	Dental applications
	83%–87%Ti–13%–17%Zr (Roxolid)	Dental applications
Stainless steel	316L	Dental, knee joint, hip joint, surgical tools
Cobalt chromium alloy	Co–Cr–Mo, Co–Ni–Cr–Mo	Artificial valve, bone fixation, dental applications, knee joint, hip joint
Shape memory alloy	NiTi	Catheters, stents
Polymers	PMMA, PE, PEEK	Dental applications, articular cartilage, hip joint bearing surface, knee joint bearing
Bio-glass	$SiO_2/CaO/Na_2O/P_2O_5$	Dental applications, orthopedic implants
Zirconia	Zirconia	Porous implants, dental applications
Alumina	Al_2O_3	Dental applications
Hydroxyapatite	$Ca_5(PO_4)_3(OH)$	Dental applications, implant coating material

Source Singh et al. (2017)

motorsport rather than in conventional automotive manufacturing. However, AM found widespread application in automotive industries similar to that in other industrial sectors for prototyping and tooling (RP/T). Using AM removes design constraints currently imposed on the automotive designer by tooling limitations (khorram Niaki and Nonino 2017). The ability to fabricate fully individualized parts has a particular impact on ergonomic design, which is based on the customer's specific requirements and comfort fit. One example here is the use of AM in Formula 1 (F1) car racing. The Renault F1 team was the first team that established a manufacturing center that uses AM. They produce a number of car parts directly with AM technology, with beneficial effects of reducing the need for assembly. For instance, brake cooling ducts were produced by AM as the geometrical complexity makes it impossible for them to be produced by conventional manufacturing methods in one piece (Kochan 2003). Figure 2.10 shows a cooling duct, the new design replaces 16 parts with 1 part.

Kingston University's electric car racing team (KU e-Racing) is emerging as a leader in the field. In 2013 and 2014, it was named the United Kingdom's highest scoring Formula Student electric team in the annual Formula Student race at Silverstone. Using AM, they were able to significantly reduce the overall weight of the car by replacing metal parts with lightweight printed plastic components. They

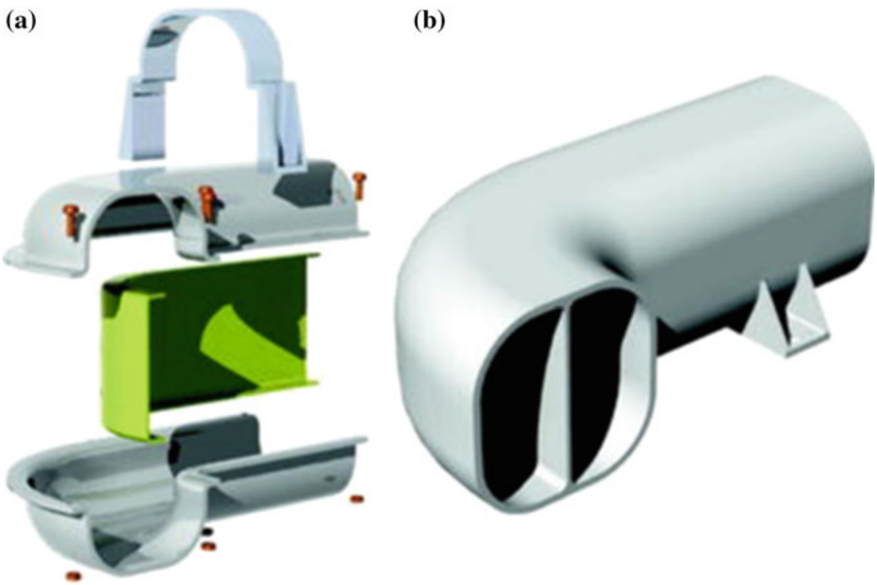


Fig. 2.10 A typical cooling duct: **a** Original design with 16 parts, **b** Integrated design. *Image Source* Gibson et al. (2010)

also 3D printed parts with the objective of fitting them directly to the car, thanks to the precision of 3DP. In the process, AM enabled the company to reduce the cost through the simultaneous manufacture of a number of production parts. It resulted in extreme reduction in labor costs and production time of around 40% compared to a conventional manufacturing process.

Thanks to AM, the company was also able to design and fabricate more complex parts than designs allowed when using conventional manufacturing because AM enables more freedom of design and increased creativity without the limitations of conventional manufacturing (see Sect. 5.1.3 for more detail). A design engineer from the team said, "With 3D printing, we could design parts that adapted to our specific needs rather than designing the car around the parts". Ku e-Racing 3D printed an exhaust fan housing in high-performance ULTEM 9085 resin, for automotive applications with its FST (flame, smoke and toxicity) rating and high strength-to-weight ratio. Moreover, the company efficiently 3D printed a variety of racing car components such as a shutdown button mounting in ABS plus thermoplastic, and an air intake system in PC-ABS. Figure 2.11 shows a complex race car upright that was fabricated by EBM in just 28 hours, demonstrating the advantage of AM for reducing time to market and increasing the flexibility.

For luxury cars with low production volumes, AM can also be economical in the manufacture of custom parts or replacement parts for antique cars. For instance, Bentley Motors produced some customer interior components, such as bezels in this fashion. Typically, Bentley production volumes for the given model are lower than

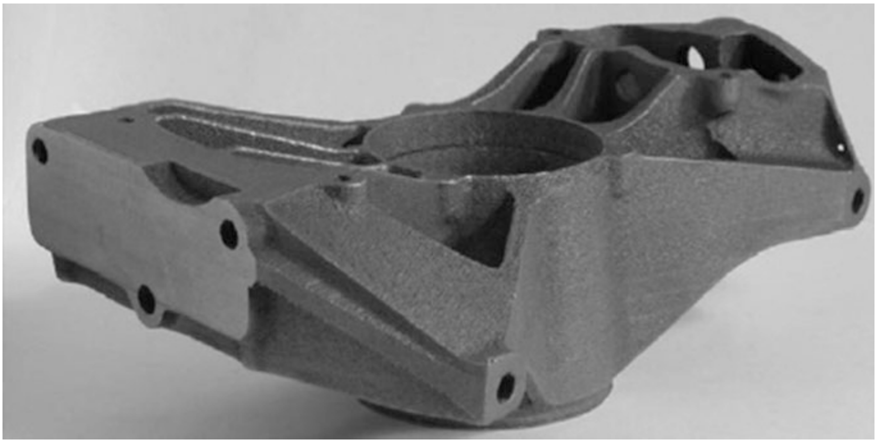


Fig. 2.11 A race car upright made by EBM. *Image Source* Petrovic et al. (2011)

10,000 cars so this could be considered as a medium production volume. Lamborghini S.p.a., a leading manufacturer of super sports cars, uses AM technologies throughout the entire lifecycle of its parts, from rapid prototyping to rapid manufacturing applications. They purchased the first 3DP (a Dimension 1200es from Stratasys) in 2003. The company mainly employed AM with the objective of rapidly fabricating parts that have complex geometries, as well as to meet the demand for high-strength production parts tough enough to endure the rigors of high-speed racing. As stated by the technical department of the company, 3D printed parts (i.e. profiles and air channel) meet the required quality level for high-performance aesthetic parts. AM also has accelerated the RP process by reducing costs and enhancing workflow efficiency. It also provides the company with a greater level of control over projects compared to the previous classic route of outsourcing the prototyping and model making. In addition, Lamborghini applied SLS of carbon fiber filled material to produce headlight washer cover flaps (Fig. 2.12) for pre-production models of the Lamborghini Gallardo for immediate delivery to dealers and customers. In these cases, AM provides a shortening of the lead time for low volume series production.

On the other hand, since the production volume in the automotive industry is usually high (100,000 per year) and commercial road vehicles have high quality requirements, AM applications are therefore being confined to RP and RT. AM has been evaluated as an expensive manufacturing technique for mass production, however, for product development processes, it brings several competitive advantages. AM enables a reduction in the time to market in a predictable manner, resulting in saved time and costs in the new product development (NPD) process. An example of this approach is the use of AM as part of a bridge-tooling process to make parts available before the full production tool is ready. Campbell et al. (2012) stated that it is obvious that AM is now a core technology for automotive product development. One of the early adopters within the industry was the Ford Motor

Fig. 2.12 Lamborghini headlight washer cover flap. *Image Source* CPR technologies

Company, which has used AM in the prototyping and testing of vehicles since the 1980s. They produced prototypes of cylinder heads, brake rotors and rear axles in a reduced time in comparison with conventional manufacturing methods and they succeeding in saving about one month of production time when creating a casting for a prototype of a complex cylinder engine head that included multiple ports, ducts, passages, and valves to manage fuel and air flow (Boulton 2013). In addition to these applications, suppliers to the automotive industry use AM parts to debug their assembly lines, and for testing their operations and tooling in order to identify potential problems before starting production. Since model line changeover involves huge investments, being able to avoid problems in production yielded very large savings (Gibson et al. 2010).

The above-mentioned areas of application include the use of AM in prototyping, tooling and small-volume high-value part production, and the advantages of each area were discussed. It is mentioned that using AM for mass production is seen as an expensive manufacturing method. However, the technology is dramatically developing in terms of size, speed and range of materials, and the growing investments from large companies in AM also demonstrate the increasing potential of this industry.

For example, Daimler AG recently funded the development of the X Line 1000R System of Concept Laser GmbH, a powder-based laser-fusing machine with a large size, for constructing metal components for vehicles and engines. The machine has a build chamber of 23.6 *15.7 * 19.7 in. (large enough to accommodate a V6 automotive engine block) and a layer thickness of 20–100 microns. In addition, the production rate of the 1000R is 65 cm^3 per hour, which is faster than other powder-based fusion 3D printers. The new machine involves a high-powered laser, allowing as much as ten times the productive capacity of other machines. Further understanding of the capability of AM came from KOR Ecologic Inc., which introduced a two-seater "green" car named the "URBEE 2" (Fig. 2.13). Its entire exterior and interior are 3D printed. "A future where 3D printers build cars may not be far off after all," said Jim Bartel, VP. An initial prototype was completed in 2013 and it became the first car to have its body 3D printed, and is the "greenest" car ever made.

Fig. 2.13 3D printed URBEE2 car body. *Image Source* KOR Ecologic Inc.

2.3.3 Aerospace

The aerospace industry, like the automotive industry was among the early adopters of AM. They adopted the technology mainly for RP from 1990s. AM has significant potential in the aerospace industry, which needs parts with complex geometries, low weights, and strength. Typically, aerospace operations involve high-value and low-volume production that is especially suited to the main benefits offered by AM. In 2012, approximately 12.1% of AM occurred in the aerospace industry. AM shipments for the U.S. aerospace industry were $29.8 million, or less than 0.05% of the U.S. aerospace industry (Ford 2014). According to Ford (2014), adopting AM technologies led to a wide variety of impacts on the aerospace industry such as a reduction in material usage, a simplified spare part supply chain, and the enabling of extremely complex geometries and integrated parts.

Reduced material usage

The idea of fabricating parts with a lattice structure in their interior to reduce weight is an issue in several industrial sectors. The strength-to-weight ratio is particularly significant in aerospace industries, where an additional 100 kg of weight, can increase the expense of an airline by more than $2.5 million in fuel over the aircraft's lifetime (Hopkinson et al. 2006). Usually, producing these structures with conventional manufacturing is difficult—or in some cases impossible. However, AM enables the direct fabrication of lattice structures with gradual and controlled porosity (Petrovic et al. 2011). Moreover, aerospace parts are very expensive and as a result they are developing a significant proportion of their parts from titanium, plastic, and other lightweight materials. The conventional processes are wasteful, sometimes exceeding 90%, while the material usage efficiency of AM is reported to be 97% (Achillas et al. 2015). According to Campbell et al. (2011) aircraft landing gear has been additively manufactured from titanium rather than cut from a titanium block, resulting in reduced material waste and costs. The buy-to-fly ratio is another indicator in this industry, which means how much material is needed to be purchased in order to manufacture the final part. The buy-to-fly rate in this industry reaches 15–20, in other words 15–20 kg are required to produce 1 kg of end product, while using AM reduces this rate to nearly 1 (Cozmei and Caloian 2012). This measure indicates that AM possesses a basic characteristic of economical operation. In another study, Reeves (2008) demonstrated that the same part, redesigned for SLM, had the same mechanical properties with 40% less material. Consequently, the advantages of AM in these cases involve reducing the use of raw materials, reducing the buy-to-fly ratio, and reducing corresponding energy consumption.

Spare part supply chain

The demand of aerospace spare parts normally follows a 20/80 Pareto curve (Liu et al, 2014). This means that 80% of the parts which are needed frequently, make most of the airline's demands. However, they only account for 20% of the supply chain expenditure in terms of holding inventory and moving materials. The supply chain of some aerospace spare parts is very slow and too unpredictable, resulting in a high cost. Therefore, many aerospace companies have applied AM technologies for these types of parts, which are high-cost long-lead components, by producing parts on-demand. Furthermore, many aerospace parts have a long useful lifecycle, therefore AM enables the use of digital models of parts instead of having to store that part itself during this long period. The impact of AM on the reduction of supply chain safety-inventory was analyzed quantitatively and the potential of AM to make the aircraft supply chain more efficient was clearly demonstrated (Walter et al. 2004; Hasan and Rennie 2008; Holmström et al. 2010). The detail of supply chain approaches, considered in light of the emergence of AM, will be discussed in Chap. 5.

Assembly requirements

Integrated parts are an ideal for the designer. However, it is impossible in some cases due to conventional design and molding constraints. Because of the freeform nature of fabrication in AM, it presents a new opportunity in optimized design for manufacturers. One industrial example of this impact has been reported by Campbell et al. (2011) who detailed how the environmental control system duct on the F-18 has been redesigned taking into account the capabilities of AM and the number of parts has been reduced from sixteen to just one. Although the conventionally manufactured assembly must have its design tailored to fit the capabilities of the machine tools used to produce the part, the AM part is built precisely to realize its function.

Complex geometry

Aeronautical components may also have more than one function. For instance, a turbine blade also has an internal structure for passing coolant through it. In addition, geometric specifications for parts may be determined by complex mathematical formulae based on fluid flow, etc. (Gibson et al. 2010). Currently, by using AM to fabricate the parts, dealing with these complexities is becoming more feasible.

A majority of companies in this sector have been using AM for many years, implementing this technology with different objectives. Rochus et al. (2007) classified these applications of AM as follows: Basic prototyping—scale models; mock-ups—geometric representations; test articles—for testing and qualification; and real flight hardware.

For instance, Boeing has used AM for the manufacture of more than 200 different components of ten aircraft platforms (Ford 2014). It has also installed over 20,000 AM parts in military and commercial aircraft (Wohlers 2014). Boing implemented thermoplastic SLS components for its 737, 747 and 777 commercial aircraft, in addition to thirty-two different components for its 787 aircraft (Freedman 2011). Boeing might only produce a small number of them during a year, therefore these were not items which have to be mass produced. Though the speed limitations of production with 3-D printing might keep it from ever producing the majority of Boeing's parts, Vander Wel says that the approach is likely to be used in a growing proportion of them. Moreover, as for metal parts, General Electric (GE Aviation), which is the world-leading provider of jet engines, invested in 2012 with the aim of developing metal AM parts for use in a gas turbine engine. GE produced a fuel nozzle for use in thousands of jet engines with AM technology (Ford 2014). The redesigned nozzle is 25% lighter and has a five times more useful lifetime than existing models, which are welded from twenty different parts (Gibson et al. 2010). In addition, the new design was engineered to reduce carbon build up, making the nozzle more efficient. The new design benefited from using less material leading to a reduction in weight, no assembly requirement and better quality. Additionally, this fuel nozzle is projected to reach a production volume of more than 100,000, where each engine contains nineteen nozzles, and GE has sold more than 4500 engines. Furthermore, GE reported that up to half of the parts in its energy and jet engines will be manufactured by AM within ten years. Figure 2.14 illustrates examples of 3D printed parts for aerospace industry including helicopters and jet engines.

Another leading aerospace company, Airbus, has additively manufactured the A320 nacelle hinge bracket, which was originally designed for steel casting. It reported that using AM for the redesigned part resulted in a 40% saving in material usage (Gibson et al. 2010). Generally, AM parts are beginning to appear on a range of Airbus aircraft, from the next-generation A350 XWB to in-service jetliners from the cornerstone A300/A310 family. Aurora Flight Sciences also fabricated and flew a 62-inch wingspan aircraft with a wing composed entirely of AM parts. Aurora expects to fabricate small, unmanned aerial vehicles, both military and civilian, within five years (Ford 2014).

Sheppard Air Force, the Trainer Development Flight (TDF) manufactures training aids that are utilized for the Air Force. The training aid can be either an original product or a replica of an existing one. Often, using these replicas is more economical for training applications, rather than using the more expensive original ones. Traditionally, TDF has used a variety of conventional manufacturing processes, such as machining, sheet metal bending and cutting, welding and lathe work, to make its products. As the production volumes were very low, the conventional method became very expensive, similar to other single or low-volume

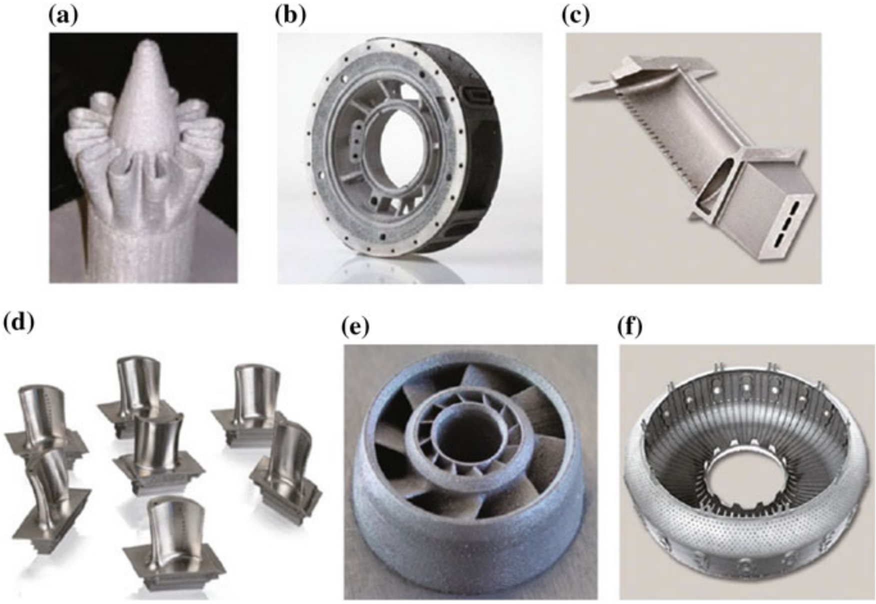


Fig. 2.14 Examples of 3D printed components for aerospace industry: **a** Mixing nozzle for gas turbine exhaust; **b** compressor support case for gas turbine engine produced by EBM; **c** turbine blade with internal cooling channels produced by SLM; **d** turbine blades fabricated by SLM; **e** hollow static turbine blade cast using the mold and cores fabricated by 3DP; **f** engine housing produced by SLM. *Image Source* Guo and Leu (2013)

production environments. Using FDM, one of the AM technologies, they could effectively manufacture many components of a replica of an unmanned aerial vehicle (UAV) such as most of the body components, several cowlings, propellers, and antennas.

According to the chief of TDF, the parts printed with FDM were durable and met their quality requirements. Moreover, it terms of environmental impacts, the process is safe and completely green producing zero waste. In terms of the profitability of investment, TDF produced the UAV's large antenna in one-tenth of the time taken by conventional manufacturing, and it delivered a return on investment (ROI) of over $12,000. Reportedly, conventional manufacturing took up to twenty days in an outsourcing process, while using FDM it takes only two days with fifteen to twenty minutes of the workforce. Generally, the impact of implementing AM in TDF was very impressive and resulted in a saving of $800,000 on the cost of projects over the four years. The CEO says, "For our first FDM machine purchase, we projected a ROI in four years, but it took only eighteen months", Weatherly says. "For our second FDM machine purchase, we saw a ROI in only nine months". In addition, TDF benefits from some other main advantages of AM, including the ability to run multiple parts simultaneously, using multiple materials for a variety of purposes, ease of maintenance, and the ability to modify designs at minimal cost.

Moreover, aside from the commercial aircraft applications, AM is an interesting manufacturing method for the space sector. In addition to all benefits mentioned above, the ability to shift the production location might be an important factor in using AM in space. It is critical when space explorers venture far from Earth and will create an on-demand supply chain for any tools and parts needed.

The National Air and Space Administration (NASA) considers AM as an essential tool for its space exploration plans, with 3D printers replicating themselves and making spare parts as well as large structures in space. Made-In-Space, a Silicon Valley start-up, prepared an AM machine that passed all NASA tests for certification. Its first zero-gravity 3D printer was delivered to the International Space Station (ISS) in 2014, and it is projected to return to Earth for further tests to verify that the 3DP works the same in microgravity as it does on Earth. Figure 2.15 shows the 3D Printer during testing in the Microgravity Science Glovebox (MSG) Engineering Unit at the Marshall Space Flight Center. NASA has also commissioned the development of 3D printers for food and for building structures on the Moon.

In addition, NASA and Pratt & Whitney Rocketdyne jointly additively manufactured a rocket engine injector, which is one of the most important and expensive components of a launch vehicle. They succeed in producing it by AM in four months and reduced costs by 70%, while conventional manufacturing took typically one year.

Fig. 2.15 Made in space 3D printer testing. *Image Source* Wikimedia

2.3.4 Consumer Goods

Theoretically, every object that is designed by computer-aided design software (CAD) can be converted to the final physical part with AM technologies using available materials. Consequently, it assists creativeness and makes the world more innovative. According to Wohlers (2012), consumer products and electronics constitute approximately 20.3% of additive manufacturing markets. This application sector will continue to growing given the development of affordable 3D printers and technological advancement. However, the prices of the machines and materials has decreased in recent years, and this is outlined in Chap. 1. For instance, the "Cubify Cube" provides a desktop 3D printer for about $1300. Nevertheless, the machine is unable to produce sturdy parts. The "MakerBot Replicator 2" is another option for home-use 3D printing. The machine is able to print in two different colors and uses materials including PLA, ABS and plastic. Nevertheless, there is an apparent need to develop better and cheaper 3D printing machines for consumer applications.

The lack of a medium in which designers would be able to directly convert their own design to the final products has existed for many years. It can be presumed that huge individual design ideas have been missed due to the lack of manufacturing facilities. AM addresses this issue and offers designers the enhanced possibility of transforming their designs into products in less time and without the need for conventional manufacturing. It also facilitates co-creation between customers and producers, and provides people with an opportunity to become micro-entrepreneurs. Simpler steps now need to be taken in order to reach the required objects, thanks to AM technology and 3D printing platforms (see Sect. 4.1.3 for more detail). Individuals can initiate a project by creating a CAD file that can be sold through AM marketplaces, such as Shapeways. Otherwise, they can modify existing CAD files that are available on websites (such as thingiverse.com) and sell 3D printed parts of these files. This will turn customers into what is called "accidental entrepreneurs" (Shah and Tripsas 2007).

AM found its own business community, the so-called Makers, which includes small business units who sell and share 3D models, 3D printed parts, and even collaborate with customers in design and production. Likewise, at the beginning of the emergence of the internet, there were many markets or internet centers facilitating the use of the internet for their customers. There are many start-ups, like Shapways, Makerbot, Materialise, etc. in this growing marketplace and they provide a variety of services (software and hardware) to their customers, from the initial ideas to the final products. These services include assisting in file preparation, optimizing design, selecting the proper technology and material, production process, and cloud-based design and production. GE Garage is another 3DP service supplier project, which began in 2012 with the objective to "reinvigorate America's interest in invention, innovation, and manufacturing" (GE 2012). GE Garage provides a platform to collaborate with designers and customers of AM. Stratasys, a leading 3D printing supplier, acquired some competitors to enter the consumer products' market. After the notable acquisition of Makerbot in 2012, Stratasys acquired Concepts Inc. and Harvest Technologies in 2014 to consolidate its portfolio in the consumer market. Inexpensive consumer 3D printers and open-source 3D designs might even change the way children play. Children can download 3D design files for the toys they want, modify and customize them as they wish, and then 3D print them in their homes.

In addition to the opportunities for self-fabrication, there are also many industrial manufactures, adopting AM for consumer goods. They may adopt whether alongside their conventional manufacturing methods or as a single manufacturing method. The following paragraphs provide examples for manufacturing of various consumer goods. 3T RPD Ltd., an AM service provider in England, fabricates its fully personalized gifts—a titanium tie clip of their customer's signature. The product's quality shows how the process deals with both angle and up-skin surfaces. Then, the very top surface of the signature is hand polished to highlight the text. This product demonstrates the individualization and customization that AM enables, likewise, another company offers the full customized bow ties (see Fig. 2.16).

Eye Venture Ltd, in collaboration with 3T RPD Ltd. developed a new product, called the ZYclip for both prescription eyewear and sunglass. Conventional manufacturing methods for the titanium-based frames included tooling, which was time consuming and expensive. Additionally, the machining process of the parts would

Fig. 2.16 Customizable bow ties

result in 95% of the material being wasted. Therefore, the company identified AM as an alternative method of manufacturing that enables them to eliminate the need for tooling and increases the flexibility in future interchangeable designs of the frames. It also was beneficial in design modifications that could be made to the CAD data, and the parts then rebuilt quickly and cost effectively. These have given Eye Venture the maximum flexibility to design eyewear frames to almost any shape or size and offer a real cost benefit over conventional manufacturing methods.

Companies are also implementing AM for the design process of this type of products. The Design Centre at Logitech Ireland Services was seeking to improve their design process and their first AM equipment was installed in 2003. The primary objectives involved testing the fit, form and function of the designed part. It enabled the design team to cost effectively explore their creative ideas and reduce the cost of design errors. Logitech employs AM throughout the design process. In concept modelling, AM enables better collaboration with the marketing department, while in the design review process, AM is used to perform fit and form testing of the given components. Finally, in production initiation, AM is used to fabricate fixtures to help in the debugging process, resulting in a cost saving on expensive machined fixtures.

Zebra Co., Ltd. has dominated the Japanese writing instruments manufacturing market. They implemented AM technologies, mostly for the purpose of new product development. Like other firms, the company had traditionally chosen outsourcing of its prototyping processes, which is not only a time-consuming and costly process, but the designers also lose the ability to rapidly modify and react to each design stage of the product development. Zebra used AM for the development of its innovative emulsion ink-based ballpoint pen, in which the smoothness of the writing experience is a key advantage of the pen, so that they could ensure the ease of grip in a minimum amount of time and at a low cost by using 3D printed prototypes that are very similar to the final products.

2.3.5 Other Industries

AM has been widely introduced in various industries, research and education centers, the arts and architecture, entertainment, machinery and equipment, and so on. The principal application sectors were discussed in previous sections, however, those cannot cover all the 3D printed markets. Thousands of case studies and examples can be made relating to all the available and attractive markets. However, we want to raise your attention by presenting some of those applications.

2.3.5.1 Architectural Models

Among the different potential applications, the most common use of AM for architecture includes the competition model and promotional models. It is possible to effectively present the idea to a jury or other professionals using a 3D printed competition model. AM is advantageous in this case because it can create a model regardless of its shape, even for one single unit. Promotional 3D printed models are a key component of virtual tours used to promote a real estate project. They allow investors or future clients to project themselves onto the area in question.

2.3.5.2 Food Industry

In the food industry and associated machinery, it can be a useful technology in the tooling and prototyping process, and even in the making of foods with a range of materials. For instance, AM technology is used to create the complex designs which are essential for machinery or complex and customized instruments used in its operation. Axon LLC manufactures the machinery used to shrink sleeve labels for containers. Most often the machines need custom tooling in order to shape the label to fit over the container. Many fixtures, called “pucks” are also required to hold the containers stable while the label is applied. Traditionally, the company produced prototype tooling, production tooling and pucks by machining them from plastic, which took approximately three weeks. The results of implementing AM in this company demonstrate a reduction of the production time from several weeks to only one day, and a production cost saving of $2400 for four pieces of tooling by a machining process, reducing down to $720 for the same parts made by 3D printing. The cost of printing a single puck is $12 compared to $125 for a machined one, a saving of about 90% on tooling costs. In addition, the manufacturer benefits from the low-cost design modification offered by AM, resulting in a better design process and final object.

Nestle Nespresso decided to buy a 3DP in 2003 in order to modernize the product development process of its coffee machines. The designers had traditionally outsourced the model making to external firms, which was a time-consuming process. It usually took several weeks to be prepared, thus any modification in design or any innovative changes were difficult to make. However, by using AM, they can now carry out any desired changes in just a few hours, something that will empower a more innovative approach—an essential factor for the development of innovative firms and products, something now possible thanks to the advent of AM. Nespresso engineers try out new ideas more often than ever before. The R&D manager said “Our creativity has grown by leaps and bounds, and we have gotten many ideas and results from the models that we created with the printer”. In addition, the company, as other AM adopters have done, utilized AM technology for function testing of its models, producing handles, brewing units, capsule holders as well as other parts of its Nespresso machines as models to be functionally tested.

Companies also made different kind of foods based on the ordered design and available ingredients using 3DP. The Fab@Home team at Cornell University developed gel-like substances (food inks) called hydrocolloids that can be extruded and built up into different shapes. By mixing in flavoring agents, they can produce a range of tastes and textures (Pearce et al. 2010). Emerging 3D printing applications include food printers that can print in cake icing, cheese, or chocolate. The food products that are formed, such as company logos, names, and other unique objects will be widely printed. Any ingredients that exists in a liquid or powder form (or can be extruded through a nozzle or syringe) can be 3D printed. This includes sugar, cheese, sauces, and many others. An entire meal comprising of pizza, an eggplant dish, corn pasta, and pannacotta was recently 3D printed.

2.3.5.3 Research and Education

There are some studies (such as Eisenberg 2013; Groenendyk and Gallant 2013; Pryor 2014) that discuss the educational benefits of AM. Thanks to AM technologies, fabrication tools are becoming available to university undergraduates, school students, and even to children. Groenendyk and Gallant (2013) investigated the implication of 3DP and scanning at Dalhousie Libraries. Similar to the computers or Internet, AM technologies have the potential to change library services significantly. Not only does it allow physical items to be stored in a digital format, but it can also physically recreate these items on-demand for library patrons. 3D printing and scanning technologies can also provide advanced techniques of data visualization, enabling researchers to present data to audiences. Libraries can play an important role in this adoption and transition, much as they have in the past through the introduction of computers and the internet.

The Department of Industrial Design at Coventry University successfully employed AM aimed at the education sector. This department has reportedly gained popularity in educational leadership and development. The department utilizes AM technologies for a wide range of design applications, including fine art, jewelry, product design and automotive design. In 2006, the department installed the "Eden250", a 3-D printing system from Stratasys. The department's design technician stated that the principal benefits that AM brings to the educational process include significantly reducing production times and the promotion of creative thinking. It also affects the design process, because conventional manufacturing had limitations, while AM enables detailed designs that are more complex. AM allows for the production of parts that are already not feasible using conventional methods. In addition, they can now print one part instead of many parts that need to be assembled.

2.3.5.4 Pharmaceutical Industry

The pharmaceutical industry is also an AM application sector. For example, they used AM technologies to fabricate a custom-made daily pill for individual patients, which eliminates the need to keep track of multiple medications. AM is used for the controlled production of complex, multicomponent oral drug delivery tablets. Hopkinson et al. (2006) explained the process as follows: “A drug concentration profile can be generated in a computer model which may be produced by AM. By this means complex drug delivery regimes can be created featuring multiple drugs or the periodical, dosed release of a single drug.” Identification markings on the pill eliminate the confusion and uncertainty of conventional medicines (Lipson 2012).

In general, three scenarios can be expected for the manufacture and distribution of on-demand 3D printed drugs (Lind et al. 2017), as follows:

- Factory, pharmacy (set dosage), patient
- Factory, patient (set dosage)
- Factory (set dosage), patient

The first scenario has a great impact on the distribution system of pharmaceuticals. In which, pharmacies are being compounded. They start with electronic prescriptions, which are a digital drawing and database of drug compounds, then the prescribed medicines can be 3D printed at a local pharmacy. In the second scenario, patients can use drug 3D printers, software, and/or apps to make their medicine at home, or the 3D drug printers can be remotely operated by healthcare professionals. In the third scenario, pharmaceutical firms will receive the patient’s information and needs so that they can produce on-demand and customized drugs. However, the societal aspects of AM implementation in the pharmaceutical industry need to be taken into account. These aspects may involve regulations (for 3D printed drugs, for 3D printers) and the requalification of pharmacies.

Many other manufacturing sectors have introduced 3D printers to print things like jewelry and to make toys for kids, ultra light and perfectly fitted shoes, custom bike frames and road cycling helmets, and custom designed electric guitars, and so on. Table 2.2 details the significant AM application sectors, examples of current applications and the principal and commonly used materials. The output of this table provides a set of functional specifications that guides the implementation process.

Table 2.2 Overview of AM application sectors

Sectors	Current applications	Materials commonly used
Aerospace	Concept modeling and prototyping, structural and non-structural production parts, low volume replacement parts, (e.g., thrust reverser doors, landing gears, gimbal eye, fuel injection nozzles)	Titanium alloys, cobalt chromium alloys, stainless steels, nickel-based alloys, polyetherimide resins
Motor vehicles	Small quantities of structural and functional components (e.g., engine exhausts, drive shafts, gearbox components, and braking system for luxury) low volume vehicles (e.g., functional components for racing vehicles) low volume, (e.g., custom run speedometer housings, shrouds and fairings for motor cycles)	Titanium alloys, cobalt chromium alloys, stainless steels, ABS
Healthcare	Fabrication of custom-made prostheses and implants, medical devices, biological chips, tissue scaffolds, living constructs, drug-screening models, and surgical planning and training apparatus	Titanium alloys, cobalt chromium alloys, stainless steels, ABS, polyamides, nylon, photopolymers
Consumer products	I.e., Toys, figurines, furniture, office accessories, musical instruments, art, jewelry, museum displays, and fashion products	ABS, PC, SS, nylon, glass-filled polyamide, epoxy resins, wax and photopolymers cobalt chromium alloys
Industrial applications	Creation of end products that apply mechanical force to perform work	Titanium alloys, cobalt chromium alloys, stainless steels, nickel-based alloys, ABS
Architecture	Modeling of structures and designs	ABS, thermoplastic polymers
Government/military	For metal parts, heat exchangers, and use in remotely piloted vehicles.	Titanium alloys, cobalt chromium alloys, stainless steels, nickel-based alloys, polyetherimide resins

Adapted from uz Zaman et al. (2017)

Seven Key Facts

- AM products and services worldwide grew at a compound annual growth rate (CAGR) of 35.2% to $4.1 billion in 2014.
- AM can generate an economic impact of $230 billion to $550 billion per year by 2025, based on reducing costs and the value of customization.
- Approximately 67% of manufacturers are already using AM technologies.
- Industries such as consumer goods (hobbies and models, arts and fashions), automotive, aerospace, healthcare, and research institutions are the main AM application sectors.
- Aerospace industries employ AM technologies for concept models and prototypes, structural and non-structural production parts, and low volume replacement parts.
- Automotive industries employ AM technologies for small quantities of structural and functional components, low-volume vehicles (functional components for racing vehicles) and low production volume (custom run speedometer housings, shrouds and fairings for motor cycles).
- Healthcare industries employ AM technologies for custom-made prostheses and implants, medical devices, living constructs, drugs and surgical planning and training apparatus.

References

Achillas, C., Aidonis, D., Iakovou, E., Thymianidis, M., & Tzetzis, D. (2015). A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. *Journal of Manufacturing Systems, 37,* 328–339.

Baur, C., & Wee, D. (2015). Manufacturing's next act. *McKinsey Quarterly*, Jun 2015.

Bogue, R. (2013). 3D printing: the dawn of a new era in manufacturing? *Assembly Automation, 33* (4), 307–311.

Boulton, C. (2013). Printing out barbies and Ford cylinders. *The Wass Street Journal*, Dow Jones & Company, Inc. http://www.wsj.com/articles/SB10001424127887323372504578469560282127852.

Campbell, I., Bourell, D., & Gibson, I. (2012). Additive manufacturing: Rapid prototyping comes of age. *Rapid Prototyping Journal, 18*(4), 255–258.

Campbell, T., Williams, C., Ivanova, O., & Garrett, B. (2011). *Could 3D printing change the world? Technologies, potential, and implications of additive manufacturing*. Washington, DC: Atlantic Council.

Cozmei, C., & Caloian, F. (2012). Additive manufacturing flickering at the beginning of existence. *Procedia Economics and Finance, 3,* 457–462.

Eisenberg, M. (2013). 3D printing for children: What to build next? *International Journal of Child-Computer Interaction, 1*(1), 7–13.

Ford, S. L. (2014). Additive manufacturing technology: Potential implications for US manufacturing competitiveness. *Journal of International Commerce and Economics*, September 2014. Available at SSRN: https://ssrn.com/abstract=2501065

Freedman, D. (2011). Layer by layer. *MIT Technology Review*. Retrieved from: https://www.technologyreview.com/s/426391/layer-by-layer/, December 19, 2015.

Giannatsis, J., & Dedoussis, V. (2009). Additive fabrication technologies applied to medicine and health care: A review. *International Journal of Advanced Manufacturing Technology, 40*(1), 116–127.

Gibson, I., Rosen, D. W., & Stucker, B. (2010). *Additive manufacturing technologies*. New York: Springer.

Goffin, J., Van Brussel, K., Martens, K., Vander Sloten, J., Van Audekercke, R., & Smet, M. H. (2001). Three-dimensional computed tomography-based, personalized drill guide for posterior cervical stabilization at C1–C2. *Spine, 26*(12), 1343–1347.

Groenendyk, M., & Gallant, R. (2013). 3D printing and scanning at the Dalhousie University libraries: A pilot project. *Library Hi Tech, 31*(1), 34–41.

Guo, N., & Leu, M. C. (2013). Additive manufacturing: Technology, applications and research needs. *Frontiers of Mechanical Engineering, 8*(3), 215–243.

Hasan, S., Rennie, A. E. W. (2008). The application of rapid manufacturing technologies in the spare parts industry. In *Nineteenth Annual International Solid Freeform Fabrication (SFF) Symposium*, August 4–8, 2008, Austin, TX, USA.

Holmström, J., Partanen, J., Tuomi, J., & Walter, M. (2010). Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. *Journal of Manufacturing Technology Management, 21*(6), 687–697.

Hopkinson, N., Hague, R., & Dickens, P. (Eds.). (2006). *Rapid manufacturing: An industrial revolution for the digital age*. Wiley.

IndustryWeek, (June 2013). *The next wave of manufacturing*. Retrieved from http://www.industryweek.com/technology/next-wave-manufacturing-human-organs.

Khorram Niaki, M., & Nonino, F. (2017). Impact of additive manufacturing on business competitiveness: A multiple case study. *Journal of Manufacturing Technology Management, 28*(1), 56–74.

Kochan, A. (2003). Rapid prototyping helps Renault F1 Team UK improve championship prospects. *Assembly Automation, 23*(4), 336–339.

Lind, J., Kälvemark Sporrong, S., Kaae, S., Rantanen, J., & Genina, N. (2017). Social aspects in additive manufacturing of pharmaceutical products. *Expert Opinion on Drug Delivery, 14*(8), 927–936.

Lipson, H. (2012). Frontiers in additive manufacturing. *Bridge, 42*(1), 5–12.

Lipson, H., & Kurman, M. (2013). *Fabricated: The new world of 3D printing*. Wiley.

Liu, P., Huang, S. H., Mokasdar, A., Zhou, H., & Hou, L. (2014). The impact of additive manufacturing in the aircraft spare parts supply chain: Supply chain operation reference (SCOR) model based analysis. *Production Planning & Control, 25*(13–14), 1169–1181.

Liu, L., Xiong, Z., Yan, Y., Zhang, R., Wang, X., & Jin, L. (2009). Multinozzle low-temperature deposition system for construction of gradient tissue engineering scaffolds. *Journal of Biomedical Materials Research. Part B, Applied Biomaterials, 88*(1), 254–263.

Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., & Marrs, A. (2013). *Disruptive technologies: Advances that will transform life, business, and the global economy* (Vol. 12). San Francisco, CA: McKinsey Global Institute.

Pearce, J. M., Blair, C. M., Laciak, K. J., Andrews, R., Nosrat, A., & Zelenika-Zovko, I. (2010). 3-D printing of open source appropriate technologies for self-directed sustainable development. *Journal of Sustainable Development, 3*(4), 17.

Petrovic, V., Vicente Haro Gonzalez, J., Jorda Ferrando, O., Delgado Gordillo, J., Ramon Blasco Puchades, J., Portoles Grinan, L. (2011). Additive layered manufacturing: Sectors of industrial application shown through case studies. *International Journal of Production Research, 49*(4), 1061–1079.

Prototype Today (February 2013). *3D printer creates ear using injectable gels*. Retrieved from http://www.prototypetoday.com/weill-cornell-medical-college/3d-printer-creates-ear-using-injectable-gels-made-of-living-cells.

Pryor, S. (2014). Implementing a 3D printing service in an academic library. *Journal of Library Administration, 54*(1), 1–10.

Quadrani, P., Pasini, A., Mattioli-Belmonte, M., Zannoni, C., Tampieri, A., Landi, E., et al. (2005). High-resolution 3D scaffold model for engineered tissue fabrication using a rapid prototyping technique. *Medical & Biological Engineering & Computing, 43*(2), 196–199.

Reeves, P. (2008). How rapid manufacturing could transform supply chains. *Supply Chain Quarterly, 2*(04), 32–336.

Rengier, F., Mehndiratta, A., von Tengg-Kobligk, H., Zechmann, C. M., Unterhinninghofen, R., Kauczor, H. U., et al. (2010). 3D printing based on imaging data: Review of medical applications. *International Journal of Computer Assisted Radiology and Surgery, 5*(4), 335–341.

Rochus, P., Plesseria, J. Y., Van Elsen, M., Kruth, J. P., Carrus, R., & Dormal, T. (2007). New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation. *Acta Astronautica, 61*(1), 352–359.

Ruffo, M., & Hague, R. (2007). Cost estimation for rapid manufacturing simultaneous production of mixed components using laser sintering. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 221*(11), 1585–1591.

Shah, S. K., & Tripsas, M. (2007). The accidental entrepreneur: The emergent and collective process of user entrepreneurship. *Strategic Entrepreneurship Journal, 1*(1–2), 123–140.

Singh, S., Ramakrishna, S., & Singh, R. (2017). Material issues in additive manufacturing: A review. *Journal of Manufacturing Processes, 25*, 185–200.

Stevens, B., Yang, Y., Mohandas, A., Stucker, B., & Nguyen, K. T. (2008). A review of materials, fabrication methods, and strategies used to enhance bone regeneration in engineered bone tissues. *Journal of Biomedical Materials Research. Part B, Applied Biomaterials, 85*(2), 573–582.

uz Zaman, U. K., Siadat, A., Rivette, M., Baqai, A. A., & Qiao, L. (2017). Integrated product-process design to suggest appropriate manufacturing technology: A review. *International Journal of Advanced Manufacturing Technology, 91*(1–4), 1409–1430.

Vandenbroucke, B., & Kruth, J. P. (2007). Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. *Rapid Prototyping Journal, 13*(4), 196–203.

Walter, M., Holmström, J., Tuomi, H., Yrjölä, H. (2004, September). Rapid manufacturing and its impact on supply chain management. In *Proceedings of the logistics research network annual conference* (pp. 9–10).

Wohlers, T. (2012). *Wohlers report 2012.* Wohlers Associates. Inc., ISBN 975442988.

Wohlers, T. (2014). *Wohlers report 2014: 3D printing and additive manufacturing state of the industry*. Fort Collins, CO, USA: Wohlers Associates Inc.

Wohlers, T. T., & Caffrey, T. (2015). Wohlers report 2015: 3D printing and additive manufacturing state of the industry annual worldwide progress report. *Wohlers Associates*.

World Economic Forum (2015). *Deep shift technology tipping points and societal impact*. Survey Report of Global Agenda Council on the Future of Software & Society.

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The Management of Additive Manufacturing
Enhancing Business Value
Khorram Niaki, M.; Nonino, F.
2018, XIV, 243 p. 124 illus., 65 illus. in color., Hardcover
ISBN: 978-3-319-56308-4