Chapter 14
Direct Digital Manufacturing

Direct digital manufacturing (DDM) is the usage of additive manufacturing technologies for production or manufacturing of end-use components. DDM is also known as "Rapid Manufacturing;" and for the purposes of this discussion, the term rapid manufacturing, as commonly used in this field, is synonymous with DDM.

Although it may seem that DDM is a natural extension of rapid prototyping, in practice this is not usually the case. Many additional considerations and requirements come into play for production manufacturing that are not important for prototyping. In this chapter, we explore these considerations through an examination of several DDM examples, distinctions between prototyping and production, and advantages of additive manufacturing for custom and low-volume production.

Many times, DDM applications have taken advantage of the geometric complexity capabilities of AM technologies to produce parts with customized geometries. In these instances, DDM is not a replacement for mass production applications, as customized geometry cannot be mass-produced using traditional manufacturing technologies. In addition, since the economics of AM technologies do not enable economically competitive high volume production for most geometries and applications, DDM is often most economical for low-volume production applications. Two major individual-specific medical applications of DDM will be discussed, from Align Technology and Siemens/Phonak, as well as several other applications that make use of the unique design freedom afforded by AM techniques. This will be followed by a discussion of the unique characteristics of AM technologies that lead to DDM.

14.1 Align Technology

Align Technology, in Santa Clara, California, is in the business of providing orthodontic treatment devices (www.aligntech.com). Their Invisalign treatments are essentially clear braces, called aligners, that are worn on the teeth (*see* Fig. 14.1). Every 1–2 weeks, the orthodontic patient receives a new set of aligners

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Fig. 14.1 Aligner from Align Technology (Courtesy Align Technology)

that are intended to continue moving their teeth. That is, every 1–2 weeks, new aligners that have slightly different shapes are fabricated and shipped to the patient's orthodontist for fitting. Over the total treatment time (several months to a year typically), the aligners cause the patient's teeth to move from their initial position to the position desired by the orthodontist. If both the upper and lower teeth must be adjusted for 6 months, then 26 different aligners are needed for one patient, assuming that aligners are shipped every 2 weeks.

The need for many different geometries in a short period of time requires a mass customization approach to aligner production. Align's manufacturing process has been extensively engineered. First, the orthodontist takes an impression of the patient's mouth with a typical dental clay. The impression is shipped to Align Technology where it is scanned using a laser digitizer. The resulting point cloud is converted into a tessellation (set of triangles) that describes the geometry of the mouth. This tessellation is separated into gums and teeth, then each tooth is separated into its own set of triangles. Since the data for each tooth can be manipulated separately, an Align Technology technician can perform treatment operations as prescribed by the patient's orthodontist. Each tooth can be positioned into its desired final position. Then, the motion of each tooth can be divided into a series of treatments (represented by different aligners). For example, if 13 different upper aligners are needed over 6 months, the total motion of a tooth can be divided into 13 increments. After manipulating the geometric information into specific treatments, aligner molds are built in one of Align's SLA-7000 stereolithography (SL) machines. The aligners themselves are fabricated by thermal forming of a sheet of clear plastic over SL molds in the shape of the patient's teeth.

The aligner development process is geographically distributed, as well as highly engineered. Obviously, the patient and orthodontist are separated from Align Technology headquarters in California. Their data processing for the aligners is performed in Costa Rica, translating customer-specific, doctor-prescribed tooth movements into a set of aligner models. Each completed dataset is transferred electronically to Align's manufacturing facility in Juarez Mexico, where the dataset is added into a build on one of their SL machines. After building the mold using SL from the dataset, the molds are thermal formed. After thermal forming, they are shipped back to Align and, from there, shipped to the orthodontist or the patient.

Between its founding in 1997 and March, 2009, over 44 million aligners have been created (www.aligntech.com). Align's SL machines are able to operate 24 h per day, producing approximately 100 aligner molds in one SLA-7000 build, with a total production capacity of 40,000 unique aligners per day. As each aligner is unique, they are truly "customized." And by any measure, 40,000 components per day is mass production and not prototyping. Thus, Align Technologies represents an excellent example of "mass customization" using DDM.

To achieve mass-customization, Align needed to overcome the time-consuming pre- and post-processing steps in SL usage. A customized version of 3D Systems Lightyear control software was developed, called MakeTray; to automate most of the build preparation. Aligner mold models are laid out, supports are generated, process variables are set, and the models are sliced automatically. Typical post-processing steps, including rinsing and post-curing can take hours. Instead, Align developed several of its own post-processing technologies. They developed a rinsing station that utilizes only warm water, instead of hazardous solvents. After rinsing, conveyors transport the platforms to the special UV post-cure station that Align developed. UV lamps provide intense energy that can post-cure an entire platform in 2 min, instead of the 30–60 min that are typical in a Post-Cure Apparatus unit. Platforms traverse the entire post-processing line in 20 min. Support structures are removed manually at present, although this step is targeted for automation. The Align Technology example illustrates some of the growing pains experienced when trying to apply technologies developed for prototyping to production applications.

14.2 Siemens and Phonak

Siemens Hearing Instruments, Inc. (www.siemens-hearing.com) and Phonak Hearing Systems are competitors in the hearing aid business. In the early 2000s, they teamed up to investigate the feasibility of using Selective Laser Sintering technology in the production of shells for hearing aids [4]. A typical hearing aid is shown in Fig. 14.2. The production of hearing aid shells (housings that fit into the ear) required many manual steps. Each hearing aid must be shaped to fit into an individual's ear. Fitting problems cause up to 1 out of every 4 hearing aids to be returned to the manufacturer, a rate that would be devastating in most other industries.

Traditionally, an impression is taken of a patient's ear, which is then used as a pattern to make a mold for the hearing aid shell. An acrylic material is then injected

Fig. 14.2 Siemens LASR® hearing aid and shell

into the mold to form the shell. Electronics, controls, and a cover plate are added to complete the hearing aid. To ensure proper operation and comfort, hearing aids must fit snugly, but not too tightly, into the ear and must remain in place when the patient talks and chews (which change the geometry of the ear).

To significantly reduce return rates and improve customer satisfaction, Siemens and Phonak sought to redesign their hearing aid production processes. Since AM technologies require a solid CAD model of the design to be produced, the companies had to introduce solid modeling CAD systems into the production process. Impressions are still taken from patients' ears, but are scanned by a laser scanner, rather than used directly as a pattern. The point cloud is converted into a 3D CAD model, which is manipulated to fine-tune the shell design so that a good fit is achieved. This CAD shell model is then exported as an STL file for processing by a SLS machine. A scanned point cloud is shown superimposed on a hearing aid model in Fig. 14.3.

Currently, Siemens Hearing Instruments produces about 250,000 hearing aids annually. In 2007, they claimed that about half of the in-the-ear hearing aids that they produce in the US are fabricated using AM technologies. Since the adoption of additive manufacturing, their hearing aid return rate has fallen dramatically with their improved design and manufacturing process.

In the mid-2000s, Siemens developed a process to produce shells using SL technology to complement their SLS fabrication capability. SL has two main advantages over SLS. First, SL has better feature detail, which makes it possible to fabricate small features on shells that aid assembly to other hearing aid components. Second, acrylate SL materials are similar to the materials originally used in the hearing aid industry (heat setting acrylates), which are biocompatible. As mentioned, Siemens originally adopted SLS fabrication; SLS has strengths in that the nylon polyamide materials typically used in SLS are biocompatible and the surface finish of SLS parts aided hearing aid retention in the ear, since the finish had a powder-bed texture.

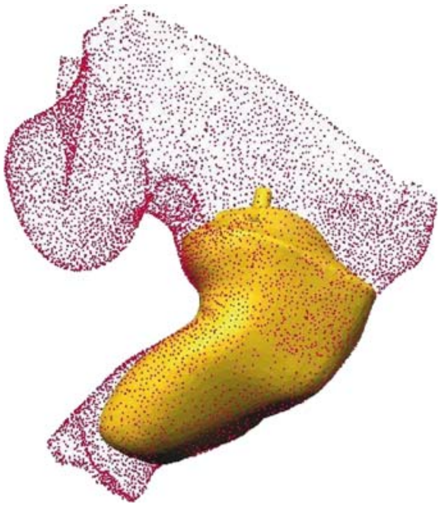

Fig. 14.3 Hearing aid within scanned point cloud

Since the introduction of AM-fabricated hearing aid shells, most hearing aid manufacturers in the Western world have adopted AM in order to compete with Siemens and Phonak. 3D Systems developed a variant of its SLA Viper Si2 machine to manufacture shells, called the SLA Viper HA. The machine contains two small vats, one with a red-tinted resin and the other with a blue-tinted resin. The idea is to fabricate both the left and right hearing aid shells for a patient in one build, where each shell is a different color, enabling the patient to easily distinguish them. Of course, the resins can be swapped with flesh-colored resin in both vats, if desired by a patient.

The hearing aid shell production is a great example of how companies can take advantage of the shape complexity capability of RP technologies to economically achieve mass customization. With improvements in scanning technology, it is likely that patients' ears can be scanned directly, eliminating the need for impressions [5]. If desktop AM systems can be developed, it may even be possible to fabricate custom hearing aids in the audiologist's office, rather than having to ship impressions or data sets to a central location!

14.3 Custom Soccer Shoes and Other DDM Examples

A British company called Prior 2 Lever (P2L) claims to be manufacturing the world's first custom soccer shoes for professional athletes. Laser sintering is used to fabricate the outsoles, including cleats, for individual customers [7]. The one-piece leather uppers are also custom tailored. A model called the Assassin retailed in 2008 for £6000 per pair; a photo is shown in Fig. 14.4. Research on SLS outsoles for custom shoes started in the early 2000s at Loughborough University; Freedom of

Fig. 14.4 Assassin model soccer shoe. Courtesy prior 2 lever

Creation and others contributed to the development of this work. Early testing demonstrated a significant reduction in peak pressures during walking and running with personalized outsoles [2]. Custom sprinting shoes and tri-athlete shoes are also being developed.

The examples presented so far all relate to body-fitting, customized parts. However, many other opportunities exist, even in the medical arena. Many companies worldwide are investigating the use of powder bed fusion technologies for the creation of orthopedic implants. For instance, Adler Ortho Group of Italy is using Arcam's EBM system to produce stock sizes of acetabular cups made from Ti–6Al–4V. The use of AM techniques enables a more compact design and a better transition between the solid bearing surface and the porous bone-ingrowth portion of the implant. Although a porous coating of titanium beads or hydroxyapatite on an implant's surface work well, they do not provide the optimum conditions for osseointegration. The hierarchical structure capabilities of AM enable the creation of a more optimal bone-ingrowth structure for osseointegration. As of early 2009, more than 1,000 "Fixa Ti-Por" cups have been implanted and more than 10,000 implants have been produced in series production.

Low volume production is often economical via AM since hard tooling does not need to be developed. This has led to the rapid adoption of DDM for low-volume components across many industries. However, the most exciting aspects of DDM are the opportunities to completely rethink how components can be shaped in order to best fulfill their functions, as discussed in Chap. 11. Integrated designs can be produced that combine several parts; eliminate assembly operations; improve performance by designing parts to utilize material efficiently; eliminate shape compromises driven by manufacturing limitations; and completely enable new styles of products to be produced. This can be true for housewares, every-day items, and even customized luxury items, as illustrated in Fig. 11.12 with respect to Freedom of Creation products. Each of these areas will be explored briefly in this section. Many of the examples were taken, or cited, in the 2008 Wohlers Report [7].

Stratasys developed a new class of FDM machines in 2007, the FDM X00mc series. They introduced the FDM 900mc in December and reported that 32 parts on the machine were fabricated on FDM machines. This is a novel example of how AM producers are using their own technologies in low volume production; and the savings that can be achieved by not having to invest in tooling. Since introducing the 900mc, Stratasys has marketed several new models, presumably using FDM parts on these models as well. This is also true for other major AM manufacturers, including EOS and 3D Systems.

The aerospace industry has been the source of quite a few successful examples of DDM. The F-18 example from Chap. 11 illustrated in Figs. 11.2 and 11.8 is one such case. In addition, SAAB Avitronics has used laser sintering to manufacture antenna RF boxes for an unmanned aircraft. Advantages of this approach over conventional manufacturing processes include a more compact design, 45% reduction in mass, and integral features. Paramount Industries produced laser sintered parts for a helicopter, including ventilation parts and electrical enclosures, and structures for unmanned aerial vehicles. The parts were manufactured on their EOSINT P 700 machine from EOS using the PA 2210 FR material (flame retardant). Additionally, hundreds of parts, or more, are flying on the space shuttle, space station, and various military aircraft.

Many of the most promising commercial aircraft applications are delayed until better flame retardant materials are certified for commercial use. However, even with the limitations of current SLS materials, Boeing has implemented thermoplastic SLS components on commercial 737, 747 and 777 programs and has several hundred components on the 787 flight test aircraft. In addition, large numbers of SLS components are present on several military derivative aircrafts, such as the Airborne Early Warning and Control (AEWC), C-40, AWACS, and P-8 aircraft. Similarly, for fighter aircraft, Northrop Grumman has identified more than 1,400 parts on a single aircraft platform that could be better made using SLS than traditional methods if a suitable material with higher-temperature properties were available.

In the automotive industry, examples of DDM are emerging. Formula 1 teams have been using AM technologies extensively on their racecars for several years. Applications include electrical housings, camera mounts, and other aerodynamic parts. Within the Renault Formula 1 team, they use over 900 parts on racecars each racing season. Indy and NASCAR teams also make extensive use of AM parts on their cars.

Several automotive manufacturers use AM parts on concept cars and for other purposes. Hyundai used SLS to fabricate flooring components for their QarmaQ concept car in 2007, with assistance from Freedom of Creation. Bentley uses SLS to produce some specialty parts that are subsequently covered in leather or wood. Others use AM to fabricate replacement parts for antique cars, including Jay Leno's famous garage (www.jaylenosgarage.com). BMW uses FDM extensively in production, as fixtures and tooling for automotive assembly.

In consumer-oriented industries, many specialty applications are beginning to emerge. Many service bureaus do DDM runs for customized or other specialty components. An interesting class of applications is emerging to bridge the virtual and physical worlds. The World of Warcraft is probably the largest on-line video game. Players can design their own characters for use in the virtual world, often adding elaborate clothing, accessories, and weapons. A company called Figure-Prints (www.figureprints.com) produces 100 mm (4 inch) tall models of such characters; one example was shown in Fig. 3.3. They use 3DP machines from ZCorp., with color printing capabilities, and sell characters for around $100 USD. Fabjectory is another company that offers a similar service, fabricating characters from the Nintendo Wii, Second Life, and Google SketchUp. Jujups offers custom Christmas ornaments, printed with a person's photograph. Again, color printers from ZCorp. are used for production. In many of these applications, AM can utilize the input data only after it has been converted to a usable form, as the original data was created to serve a visual purpose and not necessarily as a representation of a true 3D object. However, software producers are beginning to consider AM as an output of their games from the outset, as is evident by the new Spore video game, which enables users to create characters that are fully defined in 3-dimensions and thus can be converted into data usable by AM technologies in a straightforward manner. Within a year after the release of the game, it was announced that players could have a 3D printout of their character, using ZCorp's technology, for less than $50 USD.

The gaming industry alone accounts for hundreds of millions of unique 3D virtual creations that consumers may want to have made into physical objects. Just as the development of computer graphics has often been driven by the gaming industry, it is appearing equally likely that the further development of color DDM technologies may also be driven by the market opportunities which are enabled by the gaming industry.

In addition to the previous lines, many other DDM applications are emerging; including in the medical and dental industries, which will be discussed further in Chap. 15. Other examples are covered in Chaps. 2, 11 and 18.

14.4 DDM Drivers

It is useful to generalize from these examples and explore how the unique capabilities of AM technologies may lead to new DDM applications. The factors that enable DDM applications include:

- Unique Shapes: parts with customized shapes.
- Complex Shapes: improved performance.
- Lot Size of One: economical to fabricate customized parts.
- Fast Turnaround: save time and costs; increase customer satisfaction.
- Digital Manufacturing: precisely duplicate CAD model.
- Digital Record: have reusable dataset.

- Electronic "Spare Parts": fabricate spare parts on demand, rather than holding inventory.
- No Hard Tooling: no need to design, fabricate, and inventory tools; economical low-volume production.

As indicated in the Align Technology and hearing aid examples, the capability to create customized, *unique geometries* is an important factor for DDM. Many AM processes are effective at fabricating platforms full of parts, essentially performing mass customization of parts. For example, 100 aligner molds fit on one SLA-7000 platform. Each has a unique geometry. Approximately 25–30 hearing aid shells can fit in the high resolution region of a SLA Viper Si2 machine. Upwards of 4,000 hearing aid shells can be built in one SLS powder bed in one build. The medical device industry is a leading – and growing – industry where DDM and rapid tooling applications are needed due to the capability of fabricating patient-specific geometries.

The capability of building parts with *complex geometries* is another benefit of DDM. Features can be built into hearing aid shells that could not have been molded in, due to constraints in removing the shells from their molds. In many cases, it is possible to combine several parts into one DDM part due to AM's complexity capabilities. This can lead to tremendous cost savings in assembly tooling and assembly operations that would be required if multiple parts were fabricated using conventional manufacturing processes. Complexity capabilities also enable new design paradigms, as discussed with respect to acetabular cups and as seen in Chap. 11. These new design concepts will be increasingly realized in the near future.

Related to the unique geometry capability of AM, economical *lot sizes of one* are another important DDM capability. Since no tooling is required in DDM, there is no need to amortize investments over many production parts. DDM also avoids the extensive process planning that can be required for machining, so time and costs are often significantly reduced. These factors and others help make small lot sizes economical for DDM.

Fast turnaround is another important benefit of DDM. Again, little time must be spent in process planning; tooling can be avoided; and AM machines build many parts at once. All these properties lead to time savings when DDM is used. It is common for hearing aid manufacturers to deliver new hearings aids in less than 1 week from the time a patient visits an audiologist. Align Technology must deliver new aligners to patients every 1–2 weeks. Rapid response to customer needs is a hallmark of AM technologies and DDM takes advantage of this capability.

The capability of *digital manufacturing*, or precisely fabricating a mathematical model, has important applications in several areas. The medical device industry takes advantage of this; hearing aid shells must fit the patient's ear canal well, the shape of which is described mathematically. This is also important in artwork and high-end housewares, where small shape changes dictated by manufacturing limitations (e.g., draft angles for injection molding) may be unwelcome. More generally, the concept of digital manufacturing enables digital archiving of the design and manufacturing information associated with the part. This information can be transferred electronically anywhere in the world for part production, which can have important implications for global enterprises.

A *digital record* is similar in many ways to the digital manufacturing capability just discussed. The emphasis here is on the capability to archive the design information associated with a part. Consider a medical device that is unique to a patient (e.g., hearing aid, foot orthotic). The part design can be a part of the patient's digital medical records, which streamlines record keeping, sharing of records, and fabricating replacement parts.

Another way of explaining digital records and manufacturing, for engineered parts, is by using the phrase "*electronic spare parts*." The air handling ducts installed on F-18 fighters as part of an avionics upgrade program may be flying for another 20 years. During that time, if replacement ducts are needed, Boeing must manufacture the spare parts. If the duct components were molded or stamped, the molds or stamps must be retrieved from a warehouse to fabricate some spares. By having digital records and no tooling, it is much easier to fabricate the spare parts using AM processes; plus the fabrication can occur wherever it is most convenient. This flexibility in selecting fabrication facilities and locations is impossible if hard tooling must be used.

As mentioned several times, the advantages are numerous and significant to not requiring *tooling* for part fabrication. Note that in cases such as Align Technology, tooling is required (a rapid tooling example, not pure DDM), but the tooling itself is fabricated when and where needed, not requiring tooling inventories. The elimination of tooling makes DDM economically competitive across many applications for small lot size production.

14.5 Manufacturing vs. Prototyping

Production manufacturing environments and practices are much more rigorous than prototyping environments and practices. Certification of equipment, materials, and personnel, quality control, and logistics are all critical in a production environment. Even small considerations like part packaging can be much different than in a prototyping environment. Table 14.1 compares and contrasts prototyping and production practices for several primary considerations [1].

Certification is critical in a production environment. Customers must have a dependable source of manufactured parts with guaranteed properties. The DDM company must carefully maintain their equipment, periodically calibrate the equipment, and ensure it is always running within specifications. Processes must be engineered and not left to the informal care of a small number of skilled technicians. Experimentation on production parts is not acceptable. Meticulous records must be kept for quality assurance and traceability concerns. Personnel must be fully trained, cross-trained to ensure some redundancy, and certified to deliver quality parts.

Most, if not all, DDM companies are ISO 9000 compliant or certified. ISO 9000 is an international standard for quality systems and practices. Most customers will require such ISO 9000 practices so that they can depend on their suppliers. Many

Table 14.1 Contrast between rapid prototyping and direct digital manufacturing[a]

Key characteristic	RP company	DDM company
Certification		
Equipment	From equipment manufacturer	Production machines and calibration equipment
Personnel	No formal testing, certification, or training typical	On-going need for certification
Practices	Trial-and-error, no formal documentation of practices	Formal testing for each critical step, periodic recertification
Quality	Basic procedures; some inspection	ISO 9000 compliance. Extensive, thorough quality system needed
Manufacturing		
System	Basic system; controls and documentation not essential	Developed system; controls and documentation required
Planning	Basic. Requires only modest part assessment	Formal planning to ensure customer requirements are met. Developed process chains, no experimentation
Scheduling and delivery	Informally managed; critical jobs can be expedited; usually only one delivery date	Sophisticated scheduling, just-in-time delivery
Personnel	Informal training, on-the-job training; certification not necessary; redundancy not essential	Formal training for certification and periodic recertification. Redundant personnel needed for risk mitigation
Vertical integration	Helpful	From customer's perspective, should be a one-stop-shop. Qualified suppliers must be lined up ahead of time to enable integration

[a]Much of this section was adapted from Brian Hasting's presentation at the 2007 SME RAPID Conference [1]

books have been written on the ISO standards so, rather than go into extensive detail here, readers should utilize these books to learn more about this topic [3].

As mentioned, personnel should be trained, certified, and periodically retrained and/or recertified. Cross-training personnel on various processes and equipment helps mitigate risks of personnel being unavailable at critical times. If multiple shifts are run, these issues become more important, since the quality must be consistent across all shifts.

Vertical integration is important, since many customers will want their suppliers to be "one stop shops" for their needs. DDM companies may rely on their own suppliers, so the supplier network may be tiered. It is up to the DDM company, however, to identify their suppliers for specialty operations, such as bonding, coating, assembly, etc., and ensure that their suppliers are certified.

The bottom line for a company wanting to break into the DDM industry is that they must become a production manufacturing organization, with rigorous practices. Having an informal, prototyping environment, even if they can produce high quality prototypes, is not sufficient for success in the current DDM industry. Standard production business practices must be adopted.

Other than general industry standards, e.g., ISO 9000, and a few limited, specific standards, e.g., AMS 4999 on Ti metal deposition, there is a significant lack of standardization in the AM industry. This lack of standards means that:

- material data reported by various companies are not comparable;
- technology users employ different process parameters to operate their equipment according to their own preferences;
- there is little repeatability of results between suppliers or service bureaus; and
- there are few specifications which can be referenced by end users to help them ensure that a product is built as-desired.

This significantly hinders the implementation of DDM to new and emerging applications. Prior to 2009, existing standards were limited in scope and/or had no dedicated technical committee to support and evolve content. In 2008, an international standards-development initiative organized by the Society of Manufacturing Engineering within ASTM International was initiated. The first meeting of the ASTM F42 committee on standards for Additive Manufacturing Technologies was held in May, 2009. This and other standards-development initiatives are critical to further accelerate the transition of AM from a collection of rapid prototyping technologies into a widely recognized and accepted set of technologies for direct digital manufacturing.

14.6 Cost Estimation

From a cost perspective, DDM can appear to be much more expensive for part manufacture than conventional, mass production processes. A single part out of a large SL or SLS machine can cost upwards of $5,000, if the part fills much of the material chamber. However, if parts are smaller, the time and cost of a build can be divided among all the parts built at one time. For small parts, such as the hearing aid shell, costs can be only several dollars or less. In this section, we will develop a simple cost model that applies to DDM. A major component of costs is the time required to fabricate a set of parts; as such, a detailed build time model will be presented.

14.6.1 Cost Model

Broadly speaking, costs fall into four main categories: machine purchase, machine operation, material, and labor costs. In equation form, this high level cost model can be expressed, on a per build basis, as:

$$\text{Cost} = P + O + M + L \tag{14.1}$$

or, on a per part basis, as

$$\text{cost} = p + o + m + l = 1/N \times (P + O + M + L) \tag{14.2}$$

where, P = machine purchase cost allocated to the build, O = machine operation cost, M = material cost, L = labor cost, N = number of parts in the build, and the lower-case letters are the per-part costs corresponding to the per-build costs expressed using capital letters. An important assumption made in this analysis is that all parts in one build are the same kind of part, with roughly the same shape and size. This simplifies the allocation of times and costs to the parts in a build.

Machine purchase and operations costs are based on the build time of the part. We can assume a useful life of the machine, denoted Y years, and apportion the purchase price equally to all years. Note that this is a much different approach than would be taken in a cash-flow model, where the actual payments on the machine would be used (assuming it was financed or leased). A typical up-time percentage needs to be assumed also. For our purposes, we will assume a 95% up-time (the machine builds parts 95% of the time during a year). Then, purchase price for one build can be calculated as:

$$P = \frac{\text{PurchasePrice} \cdot T_b}{0.95 \cdot 24 \cdot 365 \cdot \text{Y}} \tag{14.3}$$

where T_b is the time for the build in hours and 24·365 represents the number of hours in a year. Operation cost is simply the build time multiplied by the cost rate of the machine, which can be a complicated function of machine maintenance, utility costs, cost of factory floor space, and company overhead, where the operation cost rate is denoted by C_o.

$$O = T_b \cdot C_o \tag{14.4}$$

Material cost is conceptually simple to determine. It is the volume, v, of the part multiplied by the cost of the material per unit mass, C_m, and the mass density, ρ, as given in (14.5). For AM technologies that use powders, however, material cost can be considerably more difficult to determine. The recyclability of material that is used, the volume fraction of the build that is made up of parts versus loose powder (in the case of powder bed techniques) and/or the powder capture efficiency of the process (in the case of powder deposition techniques) will result in the need to multiply the volume, v, of the part by a factor ranging from a low of 1.0 to a number as high as 7.0 to accurately capture the true cost of material consumed. Thus, for powder processes where the build material is not 100% recyclable, material cost has a complex dependency on the recyclability of the material used; the fraction of the build volume made up of parts versus loose powder; and/or the powder capture efficiency of the process. The term k_r will be introduced for the purpose of modeling the additional material consumption that considers these factors. In addition, for processes that require support materials (such as FDM and SL), the volume and cost of the supports needed to create each part must also be taken into account. The factor k_s takes this into account for such processes; typical values would range from 1.1 to 1.5 to include the extra material volume needed for supports. As a result, the model described in (14.5) will be used for material cost.

$$M = k_s \cdot k_r \cdot N \cdot v \cdot C_m \cdot \rho \tag{14.5}$$

Labor cost is the time required for workers to set up the build, remove fabricated parts, clean the parts, clean the machine, and get the machine ready for the next build.

$$L = T_l \cdot C_l \tag{14.6}$$

14.6.2 Build Time Model

The major variable in this cost model is the build time of the parts. Build time (T_b) is a function of part size, part shape, number of parts in the build, and the machine's build speed. Viewed slightly differently, build time is the sum of scan or deposition time (T_s), recoat time (T_r), and delay time (T_e):

$$T_b = T_s + T_r + T_e \tag{14.7}$$

For this analysis, we will assume that we are given the part size in terms of its volume, v, and its bounding box, aligned with the coordinate axes: bb_x, bb_y, bb_z. Recoat time is the easiest to deal with. The processes that build in material beds or vats have to recoat or deposit more material between layers; other processes do not need to recoat and have a T_r of 0. Recoat times for building support structures can be different than times for recoating when building parts, as indicated by (14.8).

$$T_r = L_s \cdot T_{rs} + L_p \cdot T_{rp} \tag{14.8}$$

where L_s is the number of layers of support structure, T_{rs} is the time to recoat a layer of support structures, L_p is the number of layers for building parts ($L_p = bb_z/LT$), T_{rp} is the recoat time for a part layer, and LT is the layer thickness.

Scan/deposition time is a function of the total cross-sectional area for each layer, the scan or fill strategy utilized, and the number of layers. Cross-sectional area depends upon the part volume and the number of parts. Scan/deposition time also depends upon whether the machine has to scan vectors to build the part in a point-wise fashion, as in SL, SLS, FDM, or the part deposits material in a wide, line-wise swath, as in ink-jet printing processes, or as a complete layer, as in layer-based photopolymerization processes. The equations are similar; we will present the build time model for scanning and leave the wide swath deposition and layer-based scanning processes for the exercises.

Now, we need to consider the part layout in the build chamber. Assuming a build platform, we have a 2D layout of parts on the platform. Parts are assumed to be of similar sizes and are laid out in a rectangular grid according to their bounding box sizes. Additionally, X and Y gaps are specified so that the parts do not touch. In the event that the parts can nest inside one another, gaps with negative values can be given. A 2D platform layout is shown in Fig. 14.5 showing the bounding boxes of 18 long, flat parts with gaps of 10 mm in the X direction and 20 mm in the Y direction. The number of parts on the platform can be computed as:

$$N = \left(\frac{PL_x + g_x - 20}{bb_x + g_x}\right)\left(\frac{PL_y + g_y - 20}{bb_y + g_y}\right) \tag{14.9}$$

where PL_x, PL_y are the platform sizes in X and Y, g_x, g_y are the X and Y gaps, and the -20 mm terms prevent parts from being built at the edges of the platform (10 mm buffer area along each platform edge). This analysis can be extended to 3D build chambers for processes which enable stacking in the z direction.

The time to scan one part depends on the part cross-sectional area, the laser or deposition head diameter d, the distance between scans h, and the average scan speed ss_{avg}. Cross-sectional area, A_{avg}, is approximated by using an area correction factor γ [6], which corrects the area based on the ratio of the actual part volume to the bounding box volume, v_{bb}, $\gamma = v/v_{bb}$. The following correction has been shown to give reasonable results in many cases.

$$A_{fn} = \gamma \cdot e^{\alpha(1-\gamma)} \tag{14.10}$$

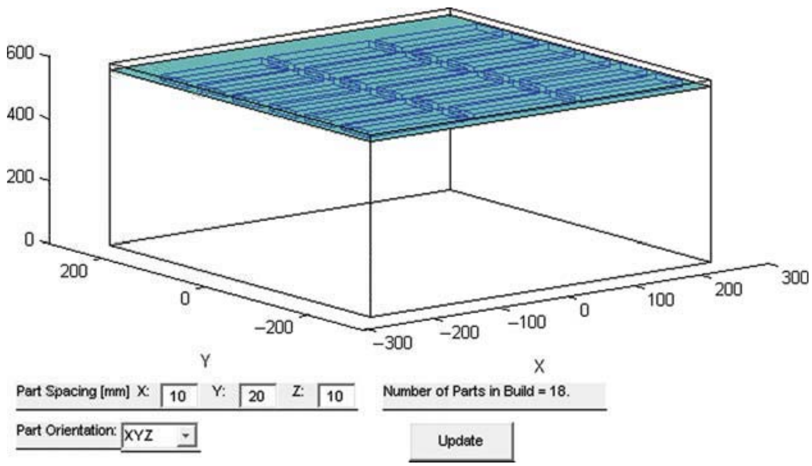

Fig. 14.5 SLA-7000 vat with 18 parts laid out on the platform

$$A_{\text{avg}} = bb_x \cdot bb_y \cdot A_{\text{fn}} \tag{14.11}$$

where α is typically taken as 1.5.

For scanning processes, it is necessary to determine the total scan length per layer. This can be accomplished by simply dividing the cross-sectional area by the diameter of the laser beam or deposited filament. Alternatively, the scan length can be determined by dividing the cross-sectional area by the hatch spacing (distance between scans). We will use the latter approach, where we take the hatch spacing, hr, to be a percentage of the laser beam diameter. For support structures, we will assume that the amount of support is a constant percentage, supfac, of the cross-sectional area (assumed as about 30%). If a process does not require supports, then the constant percentage can be taken as 0. The final consideration is the number of times a layer is scanned to fabricate a layer, denoted n_{st}. For example, in stereolithography, both X and Y scans are performed for each layer, while in FDM, only one scan is performed to deposit material. Scan length for one part and its support structure is determined using (14.12):

$$sl = A_{\text{avg}} \left(\frac{n_{\text{st}} L_{\text{p}}}{hr \cdot d} + \text{supfac} \frac{L_{\text{s}}}{d} \right) \tag{14.12}$$

The final step in determining scan/deposition time is to determine scan speed. This is a function of how fast the laser or deposition head moves when depositing material, ss_{s}, as well as when moving (jumping) between scans, ss_{j}. In some cases, jump speed is much higher than typical scan speeds. To complicate this matter, many machines have a wide range of scan speeds that depend on several part building details. For example, new SL machines have scan speeds that range from 100 to 25,000 mm/s. For our purposes, we will assume a typical scan speed that is half of the maximum speed. The average scan/deposition speed will be corrected using the area correction factor from the previous section [6] as

$$ss_{\text{avg}} = ss_{\text{s}} \cdot \gamma + ss_{\text{j}}(1 - \gamma) \tag{14.13}$$

With the intermediate terms determined, we can compute the scan/deposition time for all parts in the build as:

$$T_{\text{s}} = \frac{N \cdot sl}{3{,}600\, ss_{\text{avg}}} \tag{14.14}$$

where the 3,600 in the denominator converts from seconds to hours.

The final term in the build time (14.7) is the delay time, T_{e}. Many processes have delays built into their operations, such as platform move time, pre-recoat delay (T_{predelay}), post-recoat delay ($T_{\text{postdelay}}$), nozzle cleaning, sensor recalibration, temperature setpoint delays (waiting for the layer to heat or cool to within a specified range), and more. These delays are often user specified and depend upon build details for a particular process. For example, in SL, if parts have many fine features, longer pre-recoat delays may be used to allow the resin to cure further, to strengthen the part, before subjecting fragile features to recoating stresses. Additionally, some processes require a start-up time, for example, to heat the build chamber or warm up a laser. This start-up time will be denoted T_{start}. For our purposes, delays will be given by (14.15), but it is important to realize that each process and machine may have additional or different delay terms.

$$T_{\text{e}} = L_{\text{p}}(T_{\text{predelay}} + T_{\text{predelay}}) + T_{\text{start}} \tag{14.15}$$

With the cost and build time models presented, we now turn to the application of these models to SL.

14.6.3 Stereolithography Example

The build time and cost models presented in Section 14.7.2 will be applied to the case of hearing aid shell manufacturing using an iPro 8000 SLA Center stereolithography machine from 3D Systems with the smallest vat. The machine parameters are given in Table 14.2. Part information will be assumed to be as follows: bounding box = 15×12×20 mm, v = 1000 mm^3. An average cross-sectional area

Table 14.2 SLA Viper Pro parameters

	Small Vat		Largest Vat
PL_x (mm)	650		650
PL_y (mm)	350		750
PL_z (mm)	300		550
*PurchasePrice ($*1000)*		700	
C_o ($/hr)		30	
C_l ($/hr)		20	
Y (yrs)		7	
	Border Vectors		Hatch Vectors
d (mm)	0.13		0.76
ss_s (mm/s)	3500		25,000
ss_j (mm/s)		2* V_{scan}	
hr (hatch) (mm)		0.5	
LT (mm)		0.05 – 0.15	
n_{st}		2	
z_{supp} (mm)		0.10	
supfac		0.3	
$T_{predelay}$ (s)		15	
$T_{postdelay}$ (s)		10	
T_{start} (hr)		0.5	
C_m ($/kg)		200	
ρ (g/cm^3)		1.1	

of 45 mm^2 will be assumed, instead of using Eqns. 14.10 and 14.11. Layer thickness for the part is 0.05 mm. Support structures are assumed to be 10 mm tall, built with 0.1 mm layer thickness. Since the shell's walls are small, most of the scans will be border vectors; thus, an average laser beam diameter of 0.21 mm is assumed. Gaps of 4 mm will be used between shells.

With these values assumed and given, the build time will be computed first, followed by the cost per shell. We start with the total number of parts on one platform

$$N = \left(\frac{650 + 4 - 20}{15 + 4}\right)\left(\frac{350 + 4 - 20}{12 + 4}\right) = 1{,}393$$

The numbers of layers of part and support structure are $L_p = 400$ and $L_s = 100$. The scan length and scan speed average can be computed as: $s_l = 349{,}290$ mm, $ss_{avg} = 6230$ mm/s (linearly interpolated based on $d = 0.21$ mm). With these quantities, the scan time is:

$$T_s = \frac{1{,}393 \cdot 349{,}290}{3{,}600 \cdot 9986.9} = 13.53\,\text{h} \tag{14.14}$$

Recoat time is

$$T_r = 6/3{,}600 \times (400 + 100) = 0.83333\,\text{h}$$

Delay times total

$$T_e = 400/3{,}600 \times (15 + 10) + 0.5 = 3.278\,\text{h}$$

Adding up the scan, recoat, and delay times gives a total build time of

$$T_b = 25.8\,\text{h}$$

Part costs can be investigated now. Machine purchase price allocated to the build is \$212. Operating cost for 25.8 hours is \$774. Material and labor costs for the build are \$245 and \$10, respectively. The total cost for the build is computed to be \$1241. With 1393 shells in the build, each shell costs about \$0.89, which is pretty low considering that the hearing aid will retail for \$400 to \$1500. However these costs do not include support removal and finishing costs, nor the life-cycle costs discussed below.

14.7 Life-Cycle Costing

In addition to part costs, it is important to consider the costs incurred over the lifetime of the part, from both the customer's and the supplier's perspectives. For any manufactured part (not necessarily using AM processes), life-cycle costs associated with a part can be broken down into six main categories: equipment cost, material cost, operation cost, tooling cost, service cost, and retirement cost. As in Sect. 14.6, equipment cost includes the costs to purchase the machine(s) used to manufacture the part. Material and operation costs are related to the actual manufacturing process and are one-time costs associated only with one particular part. For most conventional manufacturing processes, tooling is required for part fabrication. This may include an injection mold, stamping dies, or machining fixtures. The final two costs, service and retirement, are costs that accrue over the life-time of the part.

This section will focus on tooling, service, and retirement costs, since they have not been addressed yet. Service costs typically include costs associated with repairing or replacing a part, which can include costs related to taking the product out of service, disassembling the product to gain access to the part, repairing or replacing the part, re-assembling the product, and possibly testing the product. Design-for-service guidelines indicate that parts needing frequent service should be easy to access and easy to repair/replace. Service-related costs are also associated with warranty costs, which can be significant for consumer products.

Let's consider the interactions between service and tooling costs. Typically, tooling is considered for part manufacture. However, tooling is also needed to fabricate replacement parts. If a certain injection molded part starts to fail in aircraft after being in service for 25 years, it is likely that no replacement parts are available "off the shelf." As a result, new parts must be molded. This requires tooling to be located or fabricated anew, refurbished to ensure it is production-worthy, installed, and tested. Assuming the tooling is available, the company would have had to store it in a warehouse for all of those years, which necessitates the construction and maintenance of a warehouse of old tools that may never be used.

In contrast, if the parts were originally manufactured using AM, no physical tooling need be stored, located, refurbished, etc. It will be necessary to maintain an electronic model of the part, which can be a challenge since forms of media become outdated; however, maintenance of a computer file is much easier and less expensive than a large, heavy tool. This aspect of life-cycle costs heavily favors AM processes.

Retirement costs are associated with taking a product out of service, dismantling it, and disposing of it. Large product dismantling facilities exist in many parts of the US and the world that take products apart; separate parts into different material streams; and separate materials for distribution to recyclers, incinerators, and landfills. The first challenge for such facilities is collecting the discarded products. A good example of product collection is a community run electronic waste collection event, where people can discard old electronic products at a central location, typically a school or mall parking lot. Product take-back legislation in Europe offers a different approach for the same objective. For automobiles, an infrastructure already exists to facilitate disposal and recycling of old cars. For most other industries, little organized product take-back infrastructure exists in the US, with the exceptions of paper and plastic food containers. In contrast to consumer products, recycling and disposal infrastructure exists for industrial equipment and wastes, particularly for metals, glass, and some plastics.

How recyclable are materials used in AM? Metals are very recyclable regardless of the method used to process it into a part. Thus, stainless steel, titanium alloys, and other metal parts fabricated in EBM, SLM, LENS, or similar systems can be recycled. For plastics, the situation is more complicated. The nylon blends used in SLS can be recycled, in principle. However, nylon is not as easily recycled as other common thermoplastics, such as the ABS or polycarbonate materials from FDM systems. Thermoset polymers, such as photopolymers in SL and printing processes, cannot be recycled. These materials can only be used as fillers, landfilled or incinerated.

In general, the issue of life-cycle costing has simple aspects to it, but is also very complicated. It is clear that the elimination of hard tooling for part manufacture is a significant benefit of AM technologies, both at the time of part manufacture and over the part's lifetime since spare parts can be manufactured when needed. On the other hand, issues of material recycling and disposal become more complicated, reflecting the various industry and consumer practices across society.

14.8 Future of Direct Digital Manufacturing

There is no question that we will see increasing utilization of AM technologies in production manufacturing. In the near-term, it is likely that new applications will continue to take advantage of the shape complexity capabilities for economical low production volume manufacturing. Longer time-frames will see emergence of applications that take advantage of functional complexity capabilities (e.g., mechanisms, embedded components) and material complexities.

To date, thousands of parts have been manufactured for the aerospace industry. Many of these parts are still flying on military aircraft, space shuttles, the International Space Station, and many satellites. Several small DDM companies have been created to serve the aerospace market. Other service bureaus revamped their operations to compete in this market. The machine vendors have reconceptualized some of their machine designs to better serve manufacturing markets. An example of this is the development of the 3D Systems SinterStation Pro, and the similar public announcements by EOS that all future models of their machines will be designed with production manufacturing in mind. Existing and start-up companies focused on AM material development are researching flame-resistant nylon materials to enable parts manufacturing for commercial aircraft, as well as higher-temperature and higher-recyclability materials.

Other markets will emerge:

- One needs only consider the array of devices and products that are customized for our bodies to see more opportunities that are similar to aligners and hearing aids. From eye glasses and other lenses to dentures and other dental restorations, to joint replacements, the need for complex, customized geometries, hierarchical structures and complex material compositions is widespread in medical and health related areas.

- New design interfaces for non-experts may one day enable individuals to design and purchase their own personal communication/computing devices (e.g., future cell phones and PDA's) in a manner similar to their current ability to have a physical representation of their virtual gaming characters produced.
- Structural components will have embedded sensors that detect fatigue and material degradation, warning of possible failures before they occur.
- The opportunities are bounded only by the imagination of those using AM technologies.

In summary, the capability to process material in an additive manner will drastically change some industries and produce new devices that could not be manufactured using conventional technologies. This will have a lasting and profound impact upon the way the products are manufactured and distributed, and thus on society as a whole. A further discussion of how DDM will likely affect business models, distributed manufacturing and entrepreneurship is contained in Chap. 18.

14.9 Exercises

1. Estimate the build time and cost for a platform of 100 aligner mold parts in a SLA-7000 machine (*see* Chap. 5). Assume that the bounding box for each part is 11 × 12 × 8 cm and the mold volume is 75,000 mm^3. Assume a scanning speed of 5,000 mm/s and a jump speed of 20,000 mm/s. All remaining quantities are given in Sect. 14.6. What is the estimated cost per mold (2 parts)?
2. A vat of hearing aid shells is to be built in a SLS Pro 140 machine (build platform size: 550 × 550 × 460 mm). How many hearing aid shells can fit in this build platform? Determine the estimated build time and cost for this build platform full of shells. Assume laser scan and jump speed of 5,000 mm/s and 20,000 mm/s, respectively. Assume the laser spot size is 0.2 mm, layer thicknesses are 0.1 mm, and only 1 scanning pass per layer is needed ($n_{st} = 1$). Assume 4 mm gaps in X, Y, and Z directions. Recall that no support structures are needed. Assume that the SLS machine needs 2 h to warm up and 2 h to cool down after the build. Assume that $T_{predelay}$ is 15 s and $T_{postdelay}$ is 2 s.
3. Develop a build time model for a jetting machine, such as the Eden models from Objet or the Invisions from 3D Systems. Note that this is a line-type process, in contrast to the point-wise vector scanning process used in SL or SLS. Consider that the jetting head can print material during each traversal of the build area and n_{st} may be 2 or 3 (e.g., 2 or 3 passes of the head are required to fully cover the total build area). Assume that $T_{predelay}$ and $T_{postdelay}$ are 2 s.
4. Estimate the build time and cost for a platform of hearing aid shells in an Eden 500 V machine (*see* Chap. 7). What is the estimated cost per shell? You will

need to visit the Objet web site and possibly contact Objet personnel in order to acquire all necessary information for computing times and costs.

5. Develop a build time model for an FDM machine from Stratasys, such as the 900mc. Note that this is a point-wise vector process without overlapping scans. Scan speeds can be up to 1,000 mm/s. Assume that a warm-up time of 0.5 h is needed to heat the build chamber. Assume that T_{predelay} and $T_{\mathrm{postdelay}}$ are 1 s.
6. Estimate the build time and cost for a platform of hearing aid shells in a 900mc FDM machine. What is the estimated cost per shell? You will need to visit the Stratasys web site and possibly contact Stratasys personnel in order to acquire all necessary information for computing times and costs.
7. Modify the model for purchase cost to incorporate net present value considerations. Rework the hearing aid shell example in Sect. 14.6.2 to use net present value. What is the estimated cost of a shell?
8. Bentley Motors has a production volume of 10,000 cars per year, over its four main models. Production volume per model per year ranges from about 200 to 4,500. Since each car may sell for $120,000 to over $500,000, each car is highly customized. Write a one-page essay on the direct digital manufacturing implications of such a business. The engines for these cars are shared with another car manufacturer; as such, do not focus your essay on the engines. Rather, focus on the chassis, interiors, and other parts of the car that customers will see and interact with.

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