AC 2007-3085: ALTERNATIVE METHODS FOR PRODUCING WIND TUNNEL MODELS FOR STUDENT PROJECTS IN FLUID MECHANICS

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Abstract

Project-based approaches to engineering education make it desirable for students to create functional wind tunnel models for testing of original designs in fluid mechanics courses. This paper compares several rapid-prototyping (RP) methods with conventional mold/cast techniques for fabrication of fluid-dynamic models on the basis of cost, production time, ease-of-use, and accessibility of equipment and materials. RP technologies considered include stereolithography (SLA), selective laser sintering (SLS), fused-deposition modeling (FDM), 3-D printing, and CNC machining. These approaches start from an original design in digital format, while conventional methods, such as casting with silicone-rubber or alginate molds require at least a rough physical prototype. Coating and finishing processes for RP models are also discussed.

Background and Introduction

The Mechanical Engineering Department at the University of Texas at Austin has been engaged for 6 years in a comprehensive program to implement project-based methods throughout the undergraduate curriculum [1]. One element of this program includes wind-tunnel testing in parallel with the introductory course in fluid mechanics. The undergraduate fluid mechanics lab houses two wind tunnels, with 12"x12" and 24"x24" test sections respectively. Currently, students use the wind tunnels only for classical experiments using off-the-shelf models such as a cylinder in a cross-flow and airfoils, and for flow visualization demonstrations. The objects being tested are simple shapes and offer limited opportunity for creative experimentation. We wish to enhance this experience by offering our students the opportunity to design and test original aerodynamic models, such as automobile body shapes. This has motivated an investigation of alternative methods for rapidly producing wind tunnel models of original designs. Two fundamentally different approaches are considered: (1) molding/casting of models starting from a rough physical prototype and (2) creation of functional physical models from a digital image.

Molding/casting techniques are capable of producing models of all sizes and geometric tolerances. These approaches can utilize a variety of different materials for both mold-making and casting, including hot melts, latex, silicone rubbers, polysulfide rubbers, polyurethane, alginate, plastic resins, epoxies, wax, foam, clay, and water based plaster or concrete. The multistep process can be lengthy and requires some skill in forming of both a reusable mold and the cast model.

Rapid prototyping (RP) refers to a process in which physical objects are fabricated directly from CAD files. This category of prototyping techniques includes processes such as stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), 3-dimensional printing, and CNC machining. Each of these processes produces durable, long lasting models which can be enhanced by a variety of secondary surface finishes. Both the equipment and the materials necessary for RP processes are expensive; nonetheless, they will consistently produce quality models requiring little in the way of manual skills.

Molding/Casting Methods

Mold making and casting are ancient processes. The development of castable and room-temperature-curable liquid polymers has made this approach simpler, more efficient, and more precise. However, producing cast models suitable for wind-tunnel testing requires skill, attention to detail, and perseverance.

All molding/casting techniques presume the existence of a physical prototype from which a mold can be produced. For wind-tunnel testing purposes, this prototype may be, for example, a clay or wood rendering of the approximate shape of the desired test model, or a plastic or metal toy airplane or car . The casting can be used directly as a finished model or can simply provide a structural base upon which the desired final aerodynamic shape can be formed by filling in with clay or other material. The most difficult part is creating an accurate, defect-free, and durable mold. Molds can be built and/or cut into several sections in order to allow for the release of the cast model. The final step requires careful filling of the mold with a casting material and then placing it in its material-specific environment for hardening.

Three of the most prevalent mold-making approaches are considered here: plaster of paris, silicone rubber, and alginate. These techniques are relatively inexpensive when compared to competing prototyping methods and are capable of producing functional models.

Plaster of Paris: Plaster of Paris (POP) is an inexpensive medium originating as a dry powder created from the dehydration of gypsum. When mixed with water, the plaster rehydrates and crystallizes into a porous solid. Being the most common of all the mold making media, POP can be bought at all local art supply and building material outlets. Mold making with POP is not difficult; however, each mold is a unique experience and suitability of this material is directly dependent on the geometry of the model [2]. Because the mold is rigid, it does not allow for any undercuts, and POP molds are unable to retain fine details that may be present in the original prototype. Molds made from POP are typically capable of producing only a few castings due to their brittleness and susceptibility to crumbling. On the plus side, POP mold making is relatively quick and leads to smooth surface finishes on the final product.

Silicone Rubber: Silicone rubber is the recommended mold-making medium for casting a wide variety of polymeric casting compounds that are available on the market, such as hot melts, latex, silicone rubbers, polysulfide rubbers, & polyurethane. Silicone rubber is commercially sold as a two part mixture whose hardening time ranges anywhere from one to thirty six hours [3]. If mixed in an even consistency, degassed, and poured carefully, silicone rubber molds can reproduce extremely fine detail and encompass complicated geometries. A mold release agent is used when casting with rubber molds to prevent sticking of the model. Silicone rubber molds generate smooth surface finishes on the final casting and are extremely durable when handled appropriately. Because they are flexible, they can accommodate some degree of undercutting in the original prototype. The strength of the mold can be reduced by chemical reactions with some casting materials and/or if left in unsuitable conditions. Silicone rubber molding kits can be purchased at most craft stores or online directly from the manufacturer. The quality of the casting is directly proportional to the time and care invested in the mold making process.

Alginate: Alginic acid, commonly known as alginate, is universally known as the cherry flavored paste the dentist uses to make detailed molds of your smile. Alginate is also used in the medical and artistic fields to make recreations of human body parts. Alginate, which originates from the cell walls of brown seaweeds, is a linear block copolymer whose physical structure can be easily arranged to recreate fine detail [4]. Similar to POP, alginate is sold in powder form which transitions into a molding paste when mixed with water. Alginate based molds typically take from a few minutes to an hour to set and are quite durable. Having a gel-like texture, alginate molds translate a smooth surface finish to the final casting. Molds are somewhat resilient and can be reused multiple times [5]. Alginate kits are considerably cheaper than silicone rubber products. Starter kits can be purchased online directly from manufacturers or through art or dental suppliers. Alginate is an easy medium to work with but you must work quickly as it sets quickly.

Comparison of molding methods: Each of the molding approaches described above has its distinct advantages and disadvantages with respect to creating wind-tunnel models for student use. Table 1 summarizes our qualitative assessment of these for each process. The bracketed refer to explanatory comments summarized in Appendix 1.

Table 1. Comparison of molding methods (Scale: 1=poor, 5=very good)

	Plaster of paris (water based) rigid mold	**Silicone rubber flexible mold**	**Alginate flexible mold**
Equipment cost [1]	5	5	5
Material cost [2]	5	4	5
Production cost [3]	5	5	5
Production time [4]	4	3	4
Prep time [5]	3	2	3
Surface finish [6]	2	3	4
Size limit [7]	3	3	3
Tensile strength [8]	2	5	4
Mold process [9]	3	2	5
Durability (product) [10]	4	4	4
Durability (mold) [11]	1	5	3
Material waste [12]	4	2	4
Availability [13]	5	5	3
Ease of use [14]	4	3	3

Example: PT-Cruiser Model Using Silicon Rubber Mold and Liquid Urethane Casting

A toy 1:24 scale die cast model of a Chrysler PT Cruiser served as the physical prototype recreated using the mold/casting technique. This car has a steeply angled front end and a blunt back end, giving rise to large step-like separation zones. Images of the original physical prototype and the final cast model are shown in Figures 1 & 2.

Figure 1-Metal prototype

Figure 2-Urethane casting

The toy prototype required some preparation to be usable as a form for the mold. Undercuts, such as the spaces between the tires and the wheel-well, had to be filled with modeling clay and the open windows had to be sealed over with smooth tape. The silicone rubber mold and urethane casting took roughly 30 hours to produce a model which stands approximately 8.5" long and 3.75" tall. The rubber mold was fabricated in two parts, allowing for a full encasement of the physical model. A single mold box was used to create both halves of the silicone mold and was also utilized to support the mold during the pouring of the liquid urethane casting resin. Applying each step of the process in the same mold box reduces the likelihood of a misalignment between the two parts of the mold, and serves as a brace for the flexible rubber. The final prototype is rigid, heavy, and has a glossy, smooth finish. A few small bubbles on surfaces of the final casting, likely caused by the release agent sprayed on the mold to prolong its life, were easily corrected with secondary finishing.

Secondary Finishes: Upon removing the final model from the silicone mold there was a small amount of excess material lining the connection between the two halves of the mold. A Dremel® tool was used to easily trim off these areas; a buffing tip allowed for controlled removal of the hard urethane material. The buffing tip also shaved down the bubbles that formed on the roof of the prototype leaving a series of small pits. Spackling putty was applied to fill the small holes; it hardens to a smooth, white finish.

Alternative casting compounds: For purposes of wind-tunnel testing, the most suitable casting compounds are urethanes and epoxies, both of which are readily available in a variety of formulations to produce the desired finished properties. Urethane resins, which have good compatibility with silicone rubber molds, are the least expensive and produce hard, machinable models with paintable surfaces. Urethane formulations are available with aluminum or fiber fillers for enhanced hardness and tensile strength. Also, either room-temperature or thermally-cured compounds can be used to obtain desired strength and both exhibit negligible shrinkage upon curing.

Epoxy casting compounds, while considerably more expensive, generally offer better strength, impact resistance, abrasion resistance, and heat-tolerance than urethanes. They are also available as either room-temperature or thermally-cured compounds; both exhibit some shrinkage upon curing.

Digital Reproduction (Rapid Prototyping) Methods

Digital reproduction methods utilize a computer-generated rendering of the desired model, virtually slice the image into cross sectional layers, and lay down successive coatings of liquid or powder material to build a physical prototype. A variety of materials can be utilized in the digital prototyping methods considered here. Working from of a computer-generated graphic, rapid-prototyping machines are capable of creating precise models in a single step with minimal manual intervention. Digital prototyping methods, however, require expensive equipment and materials. These costs must be balanced by the value of reduced time and labor. Also, little or no material is wasted in most processes and excess material can be recycled. Several digital reproduction methods are considered, including stereolithography, selective laser sintering, fused deposition modeling, 3-D printing, and CNC machining.

Stereolithography: Stereolithography (SLA) is the pioneer in digital rapid prototyping methods and is still widely used. This process builds plastic prototypes by employing a laser to cure a liquid photopolymer. The photopolymer is solidified by the laser beam forming one cross sectional layer of the final product at a time. After each layer has hardened, the work piece is lowered the depth of one layer, allowing fresh polymer to be coated over the earlier work [6]. SLA is relatively inexpensive when compared to other digital techniques and produces models at moderate speeds. These machines are capable of fabricating accurate models in both large and small scales. The main disadvantage of the SLA technique comes during the post processing stage. Surface finishes tend to be rough in texture and prototypes can be quite brittle. This process requires a stage of post-curing because the laser beam used is not powerful enough to cure an entire solid model. Various secondary finishes can be applied to enhance the overall surface finish.

Selective Laser Sintering: SLS machines use a high powered laser beam to selectively solidify the working medium in vertical cross sectional layers. SLS materials originate in a powder state and include nylon, elastomers, waxes, and metals. SLS prototypes are typically stronger than those created by SLA machines. The process is relatively slow and the surface finish tends to be coarse and powdery. Secondary finishes are available and can be used to enhance the surface finish and add to the strength of the model. The materials used in the SLS technique can be reasonably priced; however, SLS machines are more expensive than any of the other digital reproduction equipment.

Fused Deposition Modeling: The fused deposition modeling (FDM) method is the least prevalent of the digital reproduction methods. This process follows the same concept as a hot glue gun. A spool of thermoplastic material is unwound and slowly extruded out of a heated nozzle. The nozzle outlines and fills in a single cross sectional layer of melted material and repeats this same process until a solid prototype is formed [6]. Each melted layer of material hardens quickly once it has been exposed to ambient temperature. The FDM process is growing in popularity due to its potential use of a wide range of desired materials. However, FDM is the slowest of the digital reproduction methods and the quality of the resulting prototype is variable. Non-uniform layers are common causing the model to become skewed. The necessary equipment and materials are rather expensive and the knowledge base is not as well-developed as with other RP methods.

3D-Printing: 3-dimensional printing is a marriage between SLS and ink jet printing. Printing materials are powder based and are bonded together by a photopolymer liquid. The image is digitally input into the machine, which then physically "prints" the prototype in layers. The print nozzles apply the photopolymer glue over the powder in the shape of a cross sectional layer of the model. The photopolymer is then scanned by an ultraviolet light to cure the photopolymer and solidify the model [6]. 3D-printers are versatile and are capable of producing suitable aerodynamic models. This technology is the cheapest of all the digital reproduction methods in terms of both equipment and materials, and is also the fastest. The primary drawback of 3-D printing is limitation on material choice. All 3D printing machines use proprietary combinations of powder (usually starch or plaster based), binder and infiltrant, and the available options tend to create relatively rough surface finishes. Secondary finishes may be applied, but this sacrifices some of the time advantage.

CNC Machining: Computer numerical control (CNC) machining differs from the digital reproduction methods described above in that it is a material removal process in contrast to a material addition process. A computer generated graphic is used by the machine to create a cutting path and the part is cut from a solid block of material to create the model. CNC machines have been around for decades and range in price depending on speed, versatility requirements and the degree of automation desired. The efficiency of the process depends on the complexity of the prototype and the number of cutting tools needed. Most all materials can be machined; however, the cutting speed varies proportionally to the hardness of the material and the amount that needs to be removed. CNC machined parts can be created with excellent surface finishes. The main disadvantages of CNC parts are the amount of wasted material, difficulty in producing models with complex geometries and fine details, and the time consumed when changing tools [7].

Comparison of Digital Reproduction Methods: Table 2 compares relative advantages and disadvantages of the digital reproduction methods described above with a view toward wind-tunnel model making. Explanatory notes corresponding to the numbers in brackets are summarized in Appendix 2.

Table 2: Comparison of Digital Reproduction Techniques (Scale: 1=poor, 5=very good)

	Stereo-litho-graphy (SLA)	Selective Laser Sintering (SLS)	Fused Deposition Modeling (FDM)	3D Printing	CNC Machin - ing
Equipment cost [1]	2	1	2	4	3
Material cost [2]	1	3	1	4	3
Production cost [3]	3	3	2	3	2
Production time [4]	3	2	1	4	3
Prep time [5]	3	3	3	3	2
Efficiency [6]	5	4	4	4	3

Surface finish [7]	5	3	2	2	5
Size limit [8]	3	3	1	3	3
Hardness [9]	5	5	5	5	5
Material waste [10]	5	5	5	5	1
Availability [11]	3	2	1	3	4
Ease of use [12]	3	3	3	3	2

Examples: Production of Automobile Body Models by SLS and 3-D Printing

The Mechanical Engineering Department owns two rapid prototyping machines which are used for a variety of teaching and research projects, a 3D-printer and a selective laser sintering (SLS) machine. We used these machines to produce two prototype wind tunnel models of typical auto body shapes, a sports utility vehicle (SUV) and a compact sedan. Different CAD software packages were employed to produce sketches of each shape, which were imported into the RP machines for fabrication.

3D-Printer Prototype: ProEngineer® design software was utilized to sketch the SUV prototype. This model is representative of a Jeep Grand Cherokee® and contains many defining features notable on most SUV-type automobiles. From the aerodynamic standpoint, the principal features are a large frontal area, sharply-angled front-end features, high ground clearance, and an abrupt rear-end dropoff. The prototype was rendered in the standard ProE format, converted to an STL file, and sent directly to the 3D-printing machine for building. A pre-build sketch and photo of the final product are seen in Figures 3 & 4.

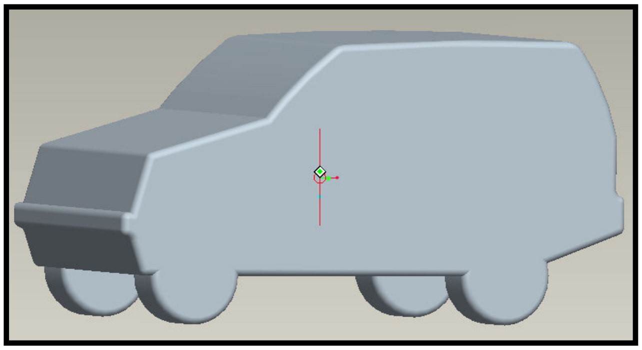

Figure 3. ProEngineer Sketch

Figure 4. 3D-Printer Model

The SUV model was constructed of ABS and was built in the "sparse" mode, meaning that the inside is hollow with several thin support frames lining the inner shell. It is 7 inches long, 4.5 inches tall, and took roughly 17 hours to build from the ground up. The model is rigid, durable, and extremely light in weight. The ABS plastic has a hard, textured finish which varies from face to face. Because the 3D-printer builds its models a horizontal cross-section at a time, surface finish on each face depends on the orientation in which the prototype sits when being built. On the SUV model, the sides were extremely smooth, while the front, back, and top exhibit a cross-hatched textured pattern. Later in this paper we will further discuss surface finishes available to smooth out the imperfections of the 3D-printer model.

Selective Laser Sintering (SLS) Prototype: Solidsworks® modeling software was used to sketch the compact sedan model which is representative of a Honda Civic® Coupe. In contrast with the SUV, this model has a relatively low profile and ground clearance, with more streamlined front and back-end features. Generating the sedan profile was more difficult than in the case of the SUV due to its more complex curved surface features. As with the previous case, the native Solidworks file was converted to STL format and sent to our SLS machine to begin the build. The original sketch and a photo of the resulting model are shown in Figures 5 & 6.

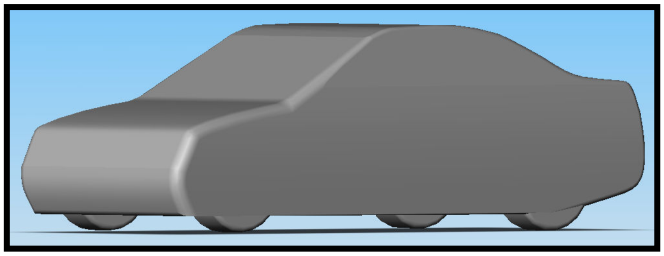

Figure 5. Solidworks Sketch

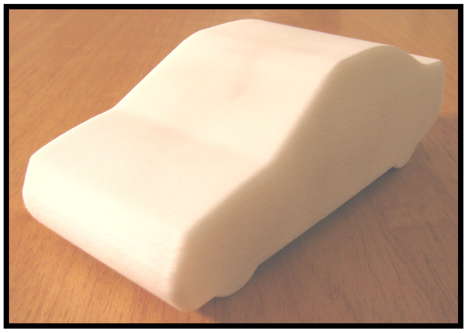

Figure 6. SLS Model

The SLS build took roughly 15 hours in which two models, approximately 7" and 10.5" in length respectively, were constructed concurrently of Duraform PA powder. The final products are rigid, hard, and dense. As with the 3D-printer, the surface finish is dependent on the orientation of the model during the build. The finish on the two sedan models was very smooth on the top and bottom faces; however the sides of the car were somewhat rough. The SLS prototypes had a somewhat chalky, soft exterior feel when compared to the 3D-printer coming out of the machine. This actually turned out to be somewhat advantageous from the standpoint of secondary surface finishing, which is discussed below.

Surface Finish

While the digital rapid prototype models we produced adequately represent the overall form characteristics sought for wind tunnel testing purposes, the surface finishes were less than perfect. This could be improved by adjusting material choice, build orientation, and operating parameters of the respective RP machines. However, secondary surface finishing is quicker and less expensive than trial-and-error testing and refabrication so we opted to try several methods, including sanding and painting or spraying water-based, acrylic, or polyurethane coatings. Eight small test blocks were quickly produced using the two RP techniques and each was treated with a surface finish product or a combination of finishes.

Sanding and painting: Sanding with a fine-grained sandpaper had a substantial effect on the smoothness of the models. Both the 3D-printed and SLS models were hard enough and thick enough that sanding produced smooth texture-free surfaces with no adverse effects on model shape or strength. The hardened Duraform powder sanded nicely and the rough faces were quickly transformed to a fine, smooth finish. Sanding provides a good foundation for additional surface finishing.

After sanding, the test blocks were painted either by airbrushing a water-based paint or brushing on an acrylic enamel. The acrylic enamel called for two coats with light sanding between, and a two hour setting time. Brush painting takes considerably more time and technique. When painting the test blocks, you could not avoid brush stroke streaks when applying a thin coat and a thick coating would leave an uneven amount of paint and texture. The final product left a nice finish but many hours were invested to get to this final appearance.

Airbrushing is a quick and controllable means of covering a lot of surface area, and when used on the test blocks, airbrushing with water-based paint produced a thin smooth finish. Since water-based paint does not adhere as well as acrylic enamel or solvent-based paints, a secondary protective coating is required to produce a durable finish.

Acrylic and Polyurethane Coating: Clear surface coatings come in a variety of types and means of application. Each of these products differs in terms of coat thickness and application/setting time. Clear coatings are available in spray-on, brush-on, dip, and pour-on forms. Like painting, brush-on coatings are susceptible to streaks and uneven texture. Dip and pour-on coatings would be difficult to use for wind tunnel models; due to their size and geometric complexity, excess coating material builds up at the corners and bottom faces during setting. We therefore chose to utilize spray-on application of acrylic and polyurethane products.

Both coating products were simple to apply and required roughly 15 – 20 minutes to initially set (12 hours for permanent set). The polyurethane spray was somewhat thicker than the acrylic per individual coat; multiple layers of each were applied to ensure a durable finish. The polyurethane coating exhibited a slightly yellowish color on the white test block whereas the acrylic finish was perfectly clear. The yellowish tint of the polyurethane was not noticeable on a dark background. Both media offered comparable results from an aerodynamic standpoint.

Costs of Commercially-Produced Rapid Prototyped Models

We have been fortunate in this project to have readily available in-house rapid-prototyping equipment and support personnel who are skilled in its use to assist us. From the data accompanying Table 2, it is evident that equipping a lab from scratch for the sole purpose of creating wind tunnel models would be prohibitively expensive. If in-house RP equipment is not available, there are a number of companies which provide rapid-prototyping services to the public. In order to utilize these services the customer must generate the graphic image of the desired model and deliver it to the prototyping company in the form of an STL file. The vendor will typically check the sketch, make necessary adjustments, determine the best build properties, and work with customers to select the most promising material to meet their needs. The prototypes produced by these organizations are of high quality (possibly higher than needed for educational purposes) and pricing can range widely depending on the process and materials selected for the build, the size and complexity of the model, and the amount of technical support required.

For comparison purposes we submitted price quotes to several prototyping service companies located through an online search. Each company's quoted price incorporates sketch adjustment, general materials, build time, and post build clean up. The car model file submitted for the price quote was 9.5 x 4 x 3.25 inches (roughly 1/20 scale). SLS-based quotes were the most expensive with prices ranging from \$2,000 – 2,500 for a single model. SLA-based models ranged from \$350 – 600 while FDM prototypes were quoted between \$650 – 800. We were unable to obtain a price quote for a 3D-printed model.

Conclusions

The methods discussed in this paper offer a range of opportunities for students in the engineering curriculum to create wind tunnel models for exploratory testing. These are not generally available off-the-shelf, so a method which will allow the student to construct a model in a reasonable period of time without a high degree of model-making experience is attractive.

From a pure cost perspective, it is clear that mold/cast methods have the advantage. Creating models in this way can give the students experience with polymer processing in addition to creating testable aerodynamic models. A variety of die-cast car models is available for use as forms, including race-cars with highly refined aerodynamics so contrasting aerodynamic characteristics can be demonstrated. The advantage of cast models is that, with some care, dozens of copies can be made from the same rubber mold, considerably reducing the cost per model. Different student groups can start with the same basic shape and revise the contour with modeling clay to effect drag reduction. The obvious down-side to cast models is that they cannot be scaled: what you see (the size of the prototype) is what you get (the model).

Digital reproduction methods offer a direct route to a functional model and give students an opportunity to apply skills in computer graphics acquired earlier in their curriculum. In the current state-of-the-art, this approach is relatively expensive, especially if the requisite equipment is not available in-house. However, aerodynamic models produced in this way are infinitely flexible and scalable. Shape changes can be made with ease and scaled to fit any size tunnel. The most time-consuming part of this approach is creating the original digital graphics file, particularly if the model is of complex shape. The time might be reduced significantly by creating a library of basic shape files that can be modified rather than requiring every student to create a file from scratch.

Perhaps the most practical economic approach for generating student models might be to produce several basic shapes in various sizes by rapid prototyping and then use them as forms to create a set of reusable molds. Students could then produce their own “customized” models by casting them in plastic and modifying them with modeling clay.

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Appendix 1: Explanatory notes for Table 1

Plaster of Paris (rigid mold):

[1] No machinery necessary; must have a mold box & mixing buckets ~$20

[2] Material cost: $4 / 4 lb bag

[3] Production cost includes original prototype, making the mold, casting the model, & necessary tools and materials

[4] Production time includes making the mold and the setting of the casting (5 - 10 hrs)

[5] Must make the mold: ~1 - 3 hr

[6] Smooth finish; poor reproduction of fine detail

[7] No max dimensions, but must provide support for large molds to prevent cracking

[8] Tensile Strength: 0.6 Mpa

[9] Mold process takes ~1 - 3 hr; much quicker than flexible molds

[10] Depends on casting material. Plaster molds can be used for most castable polymers.

[11] Brittle and susceptible to cracking/crumbling

[12] Some material is wasted in the making of a mold, but plaster is very cheap; because molds are fragile, may require several molds to make multiple models

[13] Materials are readily available at all craft and building supply stores

[14] Little experience required; some trial & error required to get consistent results

Silicone Rubber (flexible mold):

[1] No machinery necessary; must have a mold box, mold release, & mixing buckets ~$30

[2] Several materials may be used for both the mold and prototype; prices range ~$20 - 60 / 2 pint mixture

[3] Production cost includes original prototype, making the mold, casting the model, & necessary tools and materials

[4] Production time includes making the mold and the setting of the casting (24 - 36 hrs)

[5] Must make the mold: ~2 - 24 hrs depending on size and particular compound used

[6] Smooth finish; accuracy of details depends on the materials used as well as how long you let the mold/prototype set

[7] No max dimensions but large models require careful support of mold to avoid distortion

[8] Tensile Strength: 10 - 75 Mpa, depending on materials used. Strong and flexible.

[9] Mold curing process may take up to 24 hours

[10] Finished mold is durable and long lasting; accuracy depends on casting resin used, experience in mold making and casting.

[11] Molds are reusable depending on complexity of model (undercuts, details), how carefully you demold the prototype and casting.

[12] Significant material can be wasted in fabricating the mold and material is expensive, so trial and error is costly. However, molds are very durable and will hold up for many castings.

[13] Materials can be found at most art and craft supply stores and online.
[14] Significant experience factor, particularly since many different formulations are available, each best suited to particular casting compounds

Alginate:

[1] No machinery necessary; must have a mold box, mold release, & mixing buckets ~$30
[2] Materials range in cost ~$8-14/lb depending on source and quantity purchased
[3] Production cost includes original prototype, making the mold, casting the model, & necessary tools and materials
[4] Production time includes making the mold and the setting of the casting (5-10 hrs), overall comparable to plaster mold
[5] Must make the mold: 1-2 hr
[6] Smooth finish; good reproduction of fine detail
[7] No max dimensions but large models require careful support of mold to avoid distortion
[8] Tensile Strength: 10 - 25 Mpa - depending on materials used
[9] Mold process takes ~0.5 - 1 hr; much quicker than other flexible molds
[10] Comparable to silicone rubber
[11] Comparable to silicone rubber
[12] Significant material can be wasted in fabricating the mold but material is inexpensive, so trial and error is not too costly.
[13] Materials are readily available on-line or in crafts stores; dental supply stores are also an option
[14] Some experience required; some trial & error required to get consistent results

Appendix 2: Explanatory notes for Table 2

Stereolithography (SLA):

[1] SLA machines range in cost from ~$75,000 - 800,000
[2] SLA materials cost $75 - 100 / pound
[3] Production cost includes an operator, post production cleaning/finish, and maintenance
[4] Production time must include the making of a CAD file, machine prep, physical prototyping (average), and finished product cleanup
[5] Must create an STL file of the prototype model and confirm feasibility of the build
[6] When building the prototype limited time is wasted, product cleanup can be a lengthy process;
[7] Finished product has a smooth finish; can be improved by secondary finishing
[8] Max dimensions: 20"x20"x20"
[9] Tensile Strength: 38 - 58 Mpa depending on finish
[10] No wasted material, machine builds only the image provided in the STL file; unused powder may be recycled
[11] SLA equipment is fairly common
[12] Not hard to use once familiar with the equipment and its capabilities; no hands-on work involved

Selective Laser Sintering (SLS):

[1] SLS machines range in cost from $150,000 - 300,000
[2] SLS materials cost ~$30 - 60 / pound
[3] Production cost includes an operator, post production cleaning/finish, and maintenance
[4] Production time must include the making of a CAD file, machine prep, physical prototyping (average/fair), and finished product cleanup
[5] Must create an STL file of the prototype model and confirm feasibility of the build
[6] When building the prototype limited time is wasted; can depend on design; secondary finish

[7] Finished product has a rough finish; can be improved by secondary finishing
[8] Max dimensions: 11"x13"x17"
[9] Tensile Strength: 38 - 44 Mpa depending on finish
[10] No wasted material, machine builds only the image provided in the STL file; uncured material can be easily removed
[11] SLS equipment is less common than SLA but has been around for a long time
[12] Not hard to use once familiar with the equipment and its capabilities; no hands-on work involved

Fused Deposition Modeling (FDM):

[1] FDM machines range in cost from $25,000 - 300,000
[2] FDM materials cost ~$115 - 185 / pound
[3] Production cost includes an operator, post production cleaning/finish, and maintenance
[4] Production time must include the making of a CAD file, machine prep, and physical prototyping (poor)
[5] Must create an STL file of the prototype model and confirm feasibility of the build
[6] When building the prototype limited time is wasted; no clean up necessary; secondary finish
[7] Accuracy of prototyping and surface finish are problematic due to uneven layers
[8] Max dimensions: 8"x8"x12"
[9] Tensile Strength: 30 - 35 Mpa - depending on material selected
[10] No wasted material, machine builds only the image provided in the STL file
[11] The least common of all the digital prototyping methods
[12] Not hard to use once familiar with the equipment and its capabilities; no hands-on work involved

3D-Printing:

[1] 3D-printers range in cost from $18,000 - 70,000
[2] 3D-printer material cost ~$5 / in^3; can be built solid or sparse
[3] Production cost includes an operator, labor time, post process finish and maintenance
[4] Production time must include the making of a CAD file, machine prep, and physical prototyping (good)
[5] Must create an STL file of the prototype model and confirm feasibility of the build
[6] When building the prototype limited time is wasted; builds 2 - 4 layers/min; no clean up necessary; secondary finish
[7] Finish is somewhat rough due to concentric line texture; can be smoothed by secondary finishing
[8] Max dimensions: 8"x8"x12"; typically use 3D-printer for smaller pieces
[9] Tensile Strength: 30 - 35 Mpa
[10] No wasted material, machine builds only the image provided in the STL file
[11] 3D printers are becoming quite common
[12] Not hard to use once familiar with the equipment and its capabilities; no hands-on work involved

CNC Machining:

[1] CNC machines range in cost form $30,000 - 125,000
[2] CNC machines can work on almost all metals, polymers, or wood
[3] Production cost includes an operator, labor time, tools, and maintenance
[4] Production time must include the making of a CAD file, machine prep, and physical prototyping (fair). Very dependent on complexity of model.
[5] Must create an STL file of the prototype model and program cutting path
[6] When cutting the prototype time is lost due to tooling changes, unusual cutting paths, and low depth of cut

[7] Finish is smooth with minor texture

[8] Max dimension depends on the capability and size of the CNC machine itself

[9] Tensile Strength: 5 - 300 Mpa - can work with a wide range of materials

[10] Significant material waste; machine starts with a block of material and cuts away; no material can be reused

[11] Standard equipment in many machine shops. Depends on complexity of desired model.

[12] Requires considerable training and experience in machine programming and operation