Physical Terrain Modeling for Geographic Visualization

Modern Technology Meets An Ancient Art Form

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Introduction

The physical terrain model, constructed from solid materials such as sand, wood, or foam have long been a favored tool for geographic visualization. Dating back to the time of Alexander the Great, physical models have been used for terrain orientation and familiarization. As reduced scale, three-dimensional representations of the terrain, they are immediately familiar to model viewers. They can be interpreted without having to decode abstract two-dimensional representations such as contours or hachures. Physical terrain models are also appealing because viewers can directly interact with terrain, touch mountaintops and trace paths of rivers through valleys. Small physical models may be handheld while larger models on tabletops may be viewed closely, farther away, or circled, providing a wide range of perspectives.

In an era filled with virtual reality and other digital interactive three-dimensional spaces, physical models may seem outdated. However, the straightforward simplicity of physical models makes them appealing and accessible. Conversely, relatively few people are trained to operate the sophisticated software for visualizing terrain. Ideally, virtual modeling and physical terrain modeling should be seen as complementary rather than competitive technologies. Together they provide natural multiple modalities and media for viewing the terrain.

Physical models have not received wide recognition or use among cartographers, although they are popular with the military, landscape architects, realtors, engineers, lawyers, and the gaming community. Three factors have inhibited the wider adoption of physical models. First, it has been difficult to obtain the terrain information necessary to construct a model, second, many models have been generated by hand, which is time-consuming and costly,[1] and third physical models are bulky, not disposable, and in many cases not recyclable. Those models constructed using automated methods required highly specialized equipment not readily accessible to cartographers.

Today, justifications for avoiding physical terrain modeling are eroding. Digital elevation data are now readily available to the general public from a number of sources, including complete coverage of the United States by the U.S.G.S. Geographic Information Systems (GIS) can manipulate and transform this data, making it suitable for modeling. In addition, the technology for constructing models has significantly advanced and become more prevalent. Advances in numerical control software for milling and routing machines have made it possible to use this data. Physical modeling is an active area of research in the manufacturing community and cartographers will benefit from these developments. The cost of model construction is falling and the number of organizations with modeling capabilities is increasing. Often a short trip across campus or across town is all that is required to find the necessary resources.

Given this progress, it is time to revisit the role of physical terrain models in cartography. This article will reintroduce the cartographic community to the world of physical terrain modeling by briefly reviewing the state of the art in manufacturing technology and addressing some of the cartographic issues associated with physical modeling.

Manufacturing Technologies for Physical Models

Physical terrain modeling technologies fall under the general manufacturing category of rapid prototyping. Within the manufacturing community, the term rapid prototyping "refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data."[2] Rapid prototyping technologies are used for small production runs, while molding technologies are more appropriate for mass production. Rapid prototyping technologies are usually divided into three classes, subtractive, additive, and formative.[3] Subtractive technologies carve material away from a solid block, additive technologies add material to create a model, and formative technologies shape materials through the application of opposing pressures. Physical terrain models are most commonly produced using subtractive or additive processes.

Subtractive Processes for Modeling

Subtractive processes for modeling, using computer numerically controlled (CNC) milling and routing machines, have been available since the 1940s.[4]

This technology was used in the production of molded plastic relief quadrangle maps by the Army Map Service (AMS), now the National Imagery and Mapping Agency. Between 1951 and the 1970s, AMS produced around 2,000 master molds and more than 2 million plastic relief reproductions.[5] While the early molds were produced from hand-modeled terrain surfaces, later models were created with Digital Terrain Elevation Data (DTED) and CNC milling. Interestingly, the elevation data that drives the virtual worlds of today has its historic roots as a more cost-effective and efficient way to generate molds for plastic relief maps.

Milling and routing machines use cutting bits that spin rapidly to carve the model from a block of material (Figure 1). They are the most flexible devices in terms of the material selection and size of the output. Most terrain models are carved from synthetic foam, but it is possible to carve them from wood, acrylic, composites, and even metal. Very large models can be created on milling and routing machines. Thermwood (http://www.thermwood.com), a leading CNC company, has options up to 20 feet long by 10 feet wide.[6] Milling and routing machines are designed to cut 2.5-dimensional surfaces and cut vertical edges. The more advanced models can cut overhanging surfaces, such as cliffs. They vary widely in cost, from a few thousand dollars to several hundred thousand dollars. The costs are dependent on the number of axes in the machine, size, speed, and materials that can be cut. A 3-axis machine is sufficient for 2.5-dimensional models without overhangs, while 5- and 7-axis machines are required for overhangs and more complex models.

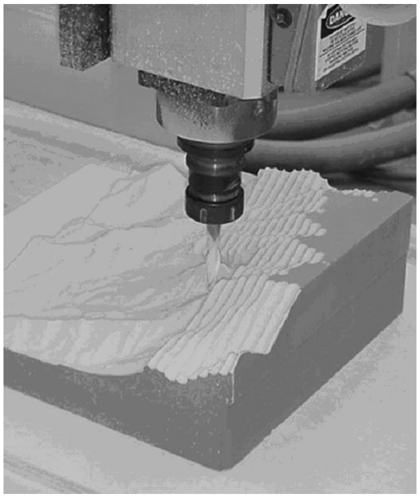

Figure 1. Physical terrain model constructed of foam and carved with a router.

This model is being cut in two passes. The first pass is a rough cut to remove excess material. This is followed by a fine cut to provide the detail for the final surface.

Credit. Physical terrain model created at the Waterways Experiment Station in Vicksburg, MS.

Additive Processes for Modeling

Additive processes for modeling are a recent innovation in manufacturing, appearing in the last fifteen years. Additive modeling is of particular interest to the manufacturing community, where complex three-dimensional models are often required. Additive modeling technologies support the generation of fully three-dimensional models, which include not only vertical edges and overhangs, but also interior holes and cavities. Additive models are usually higher resolution than subtractive models. Additive modeling systems typically cost tens of thousands of dollars, but the costs are coming down rapidly.

Currently, additive process systems do not support models with large footprints and each particular system is linked to a single material or limited range of materials. Despite these current limitations, additive modeling technologies are being constantly improved and will play an increasingly important role in terrain modeling. There are four basic processes for additive modeling: selective curing, selective sintering, aimed deposition, and bond-first pattern lamination.[7]

Selective curing uses a liquid resin, which is hardened by light from a laser or masked lamp. Stereolithography, a form of selective curing, was the first additive technology developed and is the benchmark by which other methods are compared.[8] The SLA Systems Series printers from 3D Systems (http://www. 3dsystems.com) are representative of selective curing systems.

A powder that melts with heat from a laser and fuses is the basis for selective sintering. Carl Deckard developed this technology at the University of Texas and obtained a patent for it in 1989. DTM Corporation (http://www.dtm-corp.com/) sells the Sinterstation product line for model production. Models can be built from plastic, metal, or ceramic.

The aimed deposition process streams material into specific locations The most common methods are drop-on-drop, which sprays ink from an inkjet printhead; and continuous, where a material is continuously sprayed through a nozzle. The Thermojet Solid Object Printer from 3D Systems employs drop-on-drop deposition and can produce models in neutral, gray, or black using Thermoplastic build material. This device has one of the smallest footprints and can create objects, which are only 10 x 7.5 x 8 inches. The Stratasys (http://www.stratasys.com/) family systems use the Fused Deposition Modeling (FDM) process of continuous aimed deposition. Models can be created from ABS (acrylonitrile/butadiene/styrene), high impact ABSi (methyl methacrylate ABS), investment casting wax, or a polymer with the elastic properties of rubber.

Bond-first pattern lamination uses a sheet of material: paper, plastic, ceramic, or metal powder. A layer of the material is bonded onto a stack and cut with a laser. In addition, the laser cuts a grid pattern in the surface of each layer to facilitate removal of the excess material. The next layer is bonded onto the previous layer and the cutting process is continued. The model is built as layer upon layer is bonded and cut. Helisys, Inc. was the initial developer of a family of machines using their patented Laminated Object Manufacturing (LOM) technology.

LOM models produce artifacts that are particularly interesting cartographically (Figure 2). When cut as a series of contours, the laser burns the edges of the contours, creating a brown color. This gives the model viewer an indicator of slope, as steeply sloped areas are darker brown and larger flat areas are white or the color of the material (Figure 3). The grid pattern, which is burned into the model, can also be turned to cartographic advantage. It can be sized and spaced so it represents a true map grid that links the model with real-world coordinates. After production, the LOM models are sealed and finished to prevent damage from handling or moisture.[9]

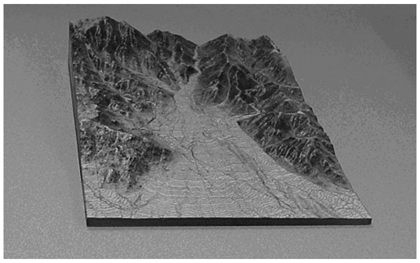

Figure 2. Laminated Object Manufacturing (LOM) model.

The Laminated Object Model (LOM) is created by bonding and cutting successive layers of paper from the bottom to the top of the model.

Credit. LOM model created by the Center for Visualization Prototypes at the San Diego Supercomputer Center, University of California at San Diego.

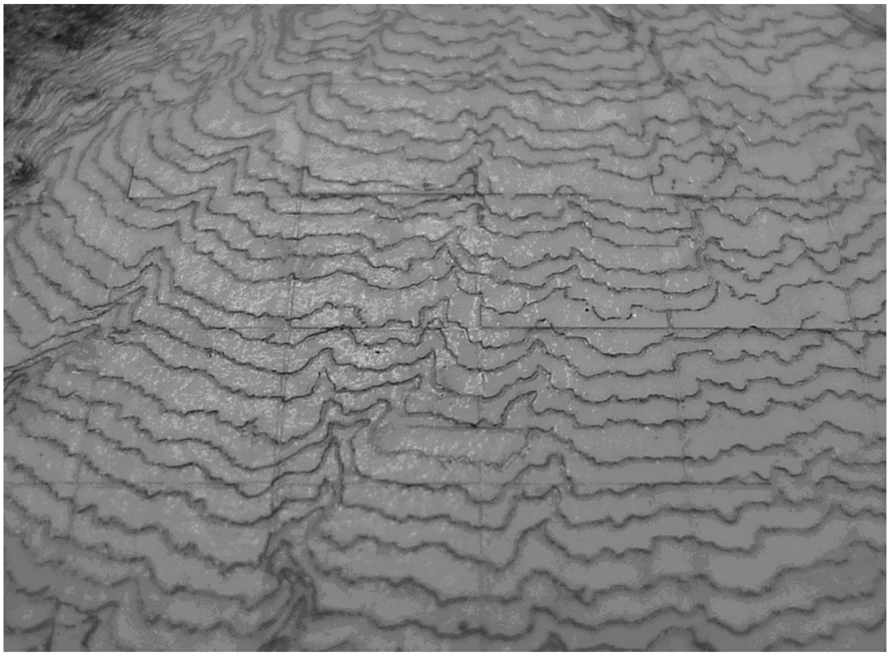

Figure 3. Close-up image of Laminated Object Manufacturing (LOM) model.

This model was built using a contour tool path. The edges of the contours are darkened as a result of being cut with a laser. The grid pattern is an artifact of the process that facilitates removal of excess material from the model.

Credit. LOM model created by the Center for Visualization Prototypes at the San Diego Supercomputer Center, University of California at San Diego.

While all the additive modeling technologies have advantages, disadvantages, and unique characteristics, bond-first pattern lamination and aimed deposition have the greatest cartographic potential. LOM models have an attractive look and feel and their unique artifacts are ideal for giving the model viewer an appreciation of the terrain. Aimed deposition technology is advancing rapidly and shows the greatest potential for eventually producing multicolor models.

The Stereolithography Format – The Lingua Franca of Physical Terrain Modeling

The goal of rapid prototyping is the automated production of models from CAD or GIS data. The data format accepted by virtually all subtractive and additive equipment manufacturers is the Stereolithography or .stl format[10]. Originally developed by 3D Systems, Inc. for their stereo-lithography equipment, the for-mat has gained broad acceptance for all technologies within the rapid prototyping community. The .stl files can be produced in either ASCII or binary format. They contain a list of the triangles with coordinates that describe the surface of the solid model. The .stl model is closely related to the Triangulated Irregular Network (TIN) model found in GIS systems, but TINs describe only the top of a model, while .stl files describe a complete surface, including the top, bottom, and sides. An .stl file can be created from gridded or tinned data using CNC CAD/CAM modeling software.

While the .stl file contains the description of the physical model, it is not usually used directly in model creation. The file is read into CNC CAD/CAM modeling software, such as Mastercam (http://www.mastercam.com/). The software converts the .stl files to machine-specific tool instructions that are used to craft the final model. In fact, this is very similar to how a map in GIS software is printed.

Cartographic Issues

Producing a physical terrain model is like creating any cartographic product. It involves planning, design, data collection, data preparation, production, and distribution processes. The model designer needs to consider the purpose of the model, the environment in which it will be displayed, and the intended audience. Based on this information the model designer makes a series of design decisions that impact the look and feel of the model. These decisions include determining the size, reso-lution, scale exaggeration, material, tool path, surface content, and finish for the model. These design decisions often affect the suitability and choice of a production method, limiting the range of appropriate and feasible technologies.

Model Size

After determining the purpose and the appropriate content for the model, the designer needs to select an appropriate size. For large models, the designer must choose between creating a single large model or tiling a number of smaller models together. Often, tiling is a more flexible solution because the individual models are stronger and less prone to warping. In addition, the design is more flexible as tiles can be added or taken away to vary the size and location of the modeled area. Routing and milling are the most appropriate rapid prototyping technologies for generating larger models, while the additive technologies are suitable for smaller models and tiled models.

Resolution

The resolution of the model is dictated by the size, intended purpose, and limitations of the manufacturing equipment. In general, smaller models will be examined more closely and should have a higher level of resolution. Larger models, which will be viewed from a distance, do not require as much detail. Additive technologies are preferable for producing higher resolution models.

Vertical Scale Exaggeration

Selecting the correct vertical exaggeration of the model is something of an art. The vertical exaggeration needs to be great enough to show relief, yet not so high as to look unrealistic. Rarely will the horizontal and vertical scales of the model be equivalent.

Todd Blyler, a model designer at the U.S. Army Topographic Engineering Center in Alexandria, VA, uses anaglyph images to assist in determining the appropriate vertical exaggeration. He creates plots of the maps at the desired horizontal scale and varies the vertical exaggeration. By viewing the plots, he has an idea of the look and feel of the final model. In addition to using anaglyph images, Mr. Blyer creates simulated versions of the model using the ERDAS Virtual GIS software. This enables him to ‘fly’ around the model and view it from different perspectives. It is an interesting twist . . . using virtual modeling techniques to assist in the specification of physical terrain models.

Terrain Characteristics

The terrain characteristics also drive the selection of the most appropriate modeling technology. Most rapid prototyping technologies can model 2.5-dimensional surfaces without multiple elevations at any location. Vertical edges and overhangs in the terrain surface require a higher level of sophistication, more commonly found in the additive processes. While the ability to create cavities is limited to the additive processes. The ability to model vertical edges is a key element in modeling urban terrain, where the underlying terrain and structures are integrated in a single surface. Alternatively, the terrain and structures can be modeled separately and the structures can be placed on the terrain model.

Material

The color and texture of material from which the model is made greatly affects the look and feel of the final product. Additive technologies like Laminated Object Manufacturing and Stereolithography have a limited range of materials that can be used in the model manufacturing process. Subtractive technologies support the widest range of materials, including wood, acrylic, composites, foams, and metal. Lightweight, durable materials should be selected. Most terrain models are created using special closed cell foams, in order to decrease their weight. Model weight concerns are especially important for larger models. The durability of the model material is also a concern because non-durable materials can chip easily.

Interesting cartographic effects are possible with the creative selection of materials. Laminated wood materials have a contoured look with the different laminated layers appearing like geological strata (Figure 4).

Tool Path

The tool path determines the direction and distance the bit, nozzle, print head, or other tool follows when creating the model. The choice of a tool path greatly affects the appearance of the resulting model. The three main alternatives are contour, profiling, or flowline paths. These are described below in terms of a routing machine, which cuts the surface down. However, the concepts are applicable to additive modeling technologies.

With a contour tool path the resulting model is a terraced surface, where the terraces are defined by the contours. This type of tool path emphasizes the shape of the terrain by incorporating the contours in the terrain surface (Figure 3). It is useful when display of terrain configuration is the primary goal of the model. This becomes a disadvantage when the model is focuses on information other than terrain, such as land cover. In this situationa profile or flowline toolpath is more appropriate.

With a profile path, the tool moves in equal steps along a profile in the x or y axis before stepping to the next profile. Profiling produces a smoother terrain surface than contouring.

The smoothest possible surface is created with a flowline tool path. Flowlines follow the terrain surface, either along equal steps of the surface distance along a profile or following the lines of steepest descent. While flowline tool paths produce the most accurate surface, profile tool paths are much faster and provide nearly identical results.

In addition to carving the terrain surface, the tool path can engrave natural and man-made features into the surface. Lawrence Faulkner, of Solid Terrain Modeling (http://www. stm-usa.com/), in Fillmore, California, makes effective use of this technique in his models. He engraves vector data in the model by cutting the paths a small distance below the terrain surface, thus integrating the vector source information with the terrain surface (Figure 5).

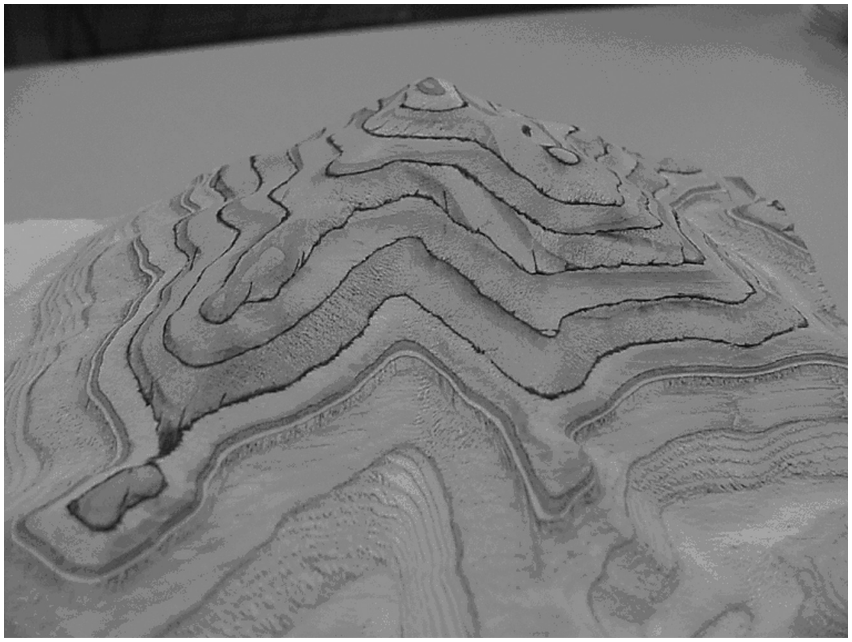

Figure 4. Model constructed from laminated wood.

The use of laminated wood for the model produces an interesting effect, giving an appearance of geological strata. However, the pattern is a function of the wood type and laminate size only. It does not represent the information in the real world.

Credit. Physical terrain model created by the Waterways Experiment Station in Vicksburg, MS.

Surface Content

After the basic model construction is completed, the designer selects information to be displayed on the surface. It can be left in its natural state, painted, or imprinted with a photographic print. Again, the choice of a particular solution depends on the intended use of the model. Laminated Object Manufacturing models, models carved from laminated wood, and models cut with contour tool paths are often left in their natural state, because they are effective at showing the terrain. The addition of information on top of the contours tends to ob-scure the contours.

Models may optionally be painted to realistically represent the natural terrain. Natural and single color models are suitable for interactive multimedia displays, where static or dynamic maps can be projected onto the surface. Mike Bailey, of the Center for Visualization Prototypes (http://cvp.sdsc.edu/) at the San Diego Supercomputer Center of the University of California at San Diego, has done innovative research on terrain models and chemical and biological models. He has developed a prototype where images are projected onto a translucent physical terrain model[11].

Model makers are also making rapid advances with printed images, such as aerial photographs, satellite images, or maps on the surfaces of physical terrain mod-

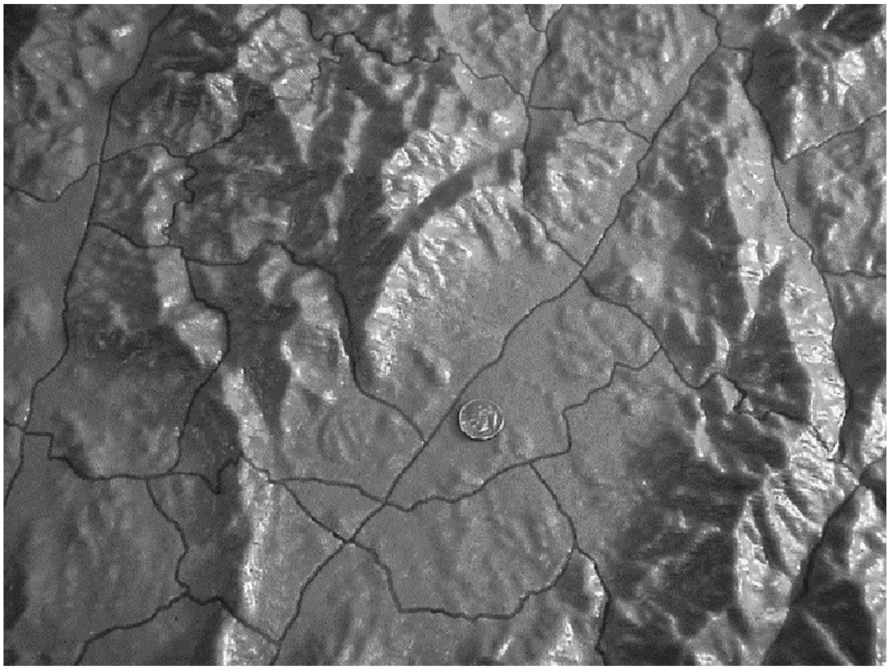

Figure 5. Physical terrain model with engraved surface.

Vector feature information can be engraved in the surface of the model, integrating the feature and elevation information.

Credit. Physical terrain model created by Solid Terrain Modeling, Inc., in Fillmore, CA.

Figure 6. Physical terrain model with photographic image printed on the surface.

Information can be painted or printed on a model. This image shows a model with a grayscale aerial photograph printed on it.

Credit. Physical terrain model created by Solid Terrain Modeling, Inc., in Fillmore, CA.

els. Both Solid Terrain Modeling, Inc. (Figure 6) and Observera (http://www.observera.com/) in Chantilly, VA, can print grayscale images on terrain models. This technique adds texture and richness to the models and is especially effective when large portions of the model are flat. Printing color images on models has been a more difficult challenge. Solid Terrain Modeling, Inc. is developing a way to print color images on the surface of a model using ink jet technology. Also, manufacturers of rapid prototyping equipment are investigating methods for creating models from multicolor materials. However, the additional printed information usually comes at the expense of a clearly defined terrain surface, which becomes slightly less discernable.

Model Finishing

In model finishing, the model designer chooses whether to coat the model surface and the type of coating material. Coating makes the surface more durable and less likely to chip. While coating is useful and often required, it does generalize the surface and reduce the detail.

With a polyester or epoxy coating on the surface the model can be annotated with a dry erase marker, enabling the surface can be reused many times. This capability is especially useful when models are used for collaborative planning.

The type of coating material affects the usability of the final model. A glossy coating reflects light off the terrain surface, making it difficult to see the underlying information when the model is viewed in an environment with overhead lights.

Production

Once the design decisions are made production can begin. Companies such as Solid Terrain Modeling, Observera, or HowardModels.com (http://www.howardmodels.com) specialize in the construction of terrain models, but any qualified rapid prototyping service bureau or manufacturer can also do production. Service bureaus, like Quickparts.com (http://www. quickparts.com), offer choices in modeling technology and can provide cost quotes and service over the Internet.

Today, model production is generally measured in hours and costs range from several hundred dollars to tens of thousands of dollars, depending on the size, material, and type of model being constructed. These costs will likely drop significantly in the next few years as the technology continues to develop and become more widely used.

Summary

Physical terrain modeling is an ancient art form that continues to be relevant.. Models provide a tangible, easily comprehended version of terrain that is immediately recognizable by viewers. Impediments to model construction, such as the difficulty in collecting data and lack of accessible automated manufacturing technology have largely been overcome. Digital elevation models are widely available and the number and variety of manufacturing technologies have significantly increased in the past decade. In addition to traditional subtractive processes, such as milling and routing, new additive processes have been invented. Technologies such as Laminated Object Manufacturing (LOM), stereolithography, and fused deposition modeling increase a modeler's production options and creates the potential for true three-dimensional modeling.

Building a model has much in common with creating a traditional map. The intended purpose of the model, the abilities of the audience, and the viewing environment are all factors to consider when developing a production strategy. GIS data can drive the production process, but the model designer must make decisions about the model size, resolution, and scale exaggeration, material, tool path, surface content, and model finishing. Production can be done by terrain modeling specialists or rapid prototyping service bureaus. The cost of model generation, now between several hundred and several thousand dollars, is continually decreasing. In the future, cartographers may view three-dimensional printing as an equally viable option for publishing their maps.

Note: Any references to companies or products is for information purposes only and does not reflect the use or endorsement of these products by the U.S. Government.

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