

Visualization of three-dimensional GIS objects using rapid prototyping technology

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Abstract

To build multicolored physical models of three-dimensional cartographic objects, such as city models, landscape with relief or conceptual surfaces, computer-controlled devices can be used which were developed for the fast and inexpensive production of mechanical parts. The main groups of rapid prototyping technology – aggregation, removal and, transformation – are presented, including the machinery to build physical models, and a new relative, laser subsurface engraving. Examples of city and surface models built by a 3D multicolor printer demonstrate the capabilities of the technology.

Virtual and physical reality

The enhanced cost-effectiveness ratio of computers and graphic peripherals has provided advanced methods to generate photo-realistic scenes, which are known as virtual reality (VR). Developers and users of geographical information systems have adopted VR to visualize spatial objects. Computer graphics and VR have also facilitated the transition from static planar maps on paper or flat displays to perspective and stereographic representations, which can also include the time dimension. Such dynamic visualization has been made possible by high-performance desktop computers and high-capacity distribution media, such as the World Wide Web, the CD-ROM and DVD.

Perspective drawings on 2D media take advantage of the viewer's lifelong experience in recognizing and interpreting depth cues in pictures. The main shortcoming of using perspective drawings for cartographic applications is the inability to obtain distances and directions from measurements in the picture, although interactive software provides solutions to that problem.

Stereoscopic displays make use of the ability of the human brain to construct a 3D mental model from two slightly different images, one corresponding to each eye. Stereo images may be provided by binocular viewers, shutter glasses, lenticular and barricade displays. Stereoscopic viewing can also be induced by non-binocular optical effects, such as SIRDS (single image random-dot stereograms) or chromostereoscopy [RASE 2003].

Despite the availability of virtual reality technology, physical models of buildings are still requested in architectural competitions, even though VR techniques are able to provide more visual information than a model. For example VR allows interiors to be visualized from different viewpoints and under varying light conditions during a walk-through, or the view through a window, in both directions, can be generated. Why are physical models still requested? One reason may be that the cost of the model is a marginal quantity compared to the cost of the competition, let alone the real building. Probably architects have also a fondness for the haptic experience, the opportunity to feel an object with their own hands.

Physical models have the advantage over 2D drawings that slight movements of the head or body suffice to compare heights, to solve viewing ambiguities or to reveal parts of the model that might be obscured in a fixed view. In case of non-dynamic media multiple drawings it may be necessary to present all parts of a scene. The quest for haptic experience may be valid not only for architects but also for decision-makers in regional planning with a limited experience in map reading. Under certain circumstances a real 3D model is able to transmit the cartographic message much better and faster than a two-dimensional map.

Rapid prototyping technology

Numerically controlled machines capable of the production of mechanical parts have been in use for more than four decades [CHUA, LEONG UND LIM 2003]. Advances in microelectronics have led to computer-controlled devices which are able to build physical models at reasonable cost within short timeframes (*rapid prototyping, RP*). The prototypes serve mainly to judge on the form and appearance, in certain cases to evaluate the mechanical function. Usually the prototypes are not exposed to the mechanical stress that their real counterparts have to withstand, for example the prototype of a steering wheel for a car. Thus it is not necessary in most cases to use the same material of which the final part will be made.

The different technical approaches for the computer-assisted production of parts can be subsumed under four headings with equivalents in the fine arts:

- Removal: A block of material is cut with a tool that removes successively small quantities of material until the final form is reached, as a block of marble is transformed into a sculpture (the *Michelangelo* method).
- Transform: The material is formed by pressure and heat, as a blacksmith forms a red-hot bar of iron (the *Chillida* method).
- Aggregation: A part is built up from small amounts of material, in the same way a sculpture or a scale model is formed in plaster or some other plastic material (the *Rodin* method).
- 3D drawing: tiny points inside a glass block are melted by a laser beam and become opaque (the *Dürer* method).

An example of the *Michelangelo* method is numerically controlled milling. Rotating tools of different size and shape moving in three and more degrees of freedom carve material from a block of metal, wood or plastic until the final form is reached. NC milling is typically slow and expensive compared to the other techniques available today. Coloring must be added in a manual process, for example by airbrushing. An exception is the production of large relief models by STM (www.stm-usa.com) using computer-controlled inkjet nozzles moving in three dimensions to apply texture on the surface. The machinery is unique and is not sold.

The transformation by heat and pressure is used to create multiple copies at moderate cost (the artist Chillida created huge metal sculptures by industrial forging of iron rods and bars). The equivalence in 2D is the printing process. In France bookstores offer terrain models of regions and *départements*, depicting height bands, rivers, streets and settlements. These models are made by transforming a thin foil of thermoplastic material by heat and pressure using a mould, in most cases produced by NC milling from a numerical representation of the relief (www.georelief.fr).

The aggregation of material, the *Rodin* method, has the greatest potential for rapid prototyping in general and for the creation of city and cartographic surface models in particular. The integration of coloring into the production process opened new horizons for cartographic applications of rapid prototyping (more in the following section).

The 3D analogy to 2D drawings is *laser subsurface engraving* which, strictly speaking, does not belong to the rapid prototyping family, but uses the same data and files to encode the model, and computer control to move the laser beam.

Printing in three dimensions

The most frequently used technologies for rapid prototyping belong to the *Aggregation* group. Stereolithography was the first technique for rapid prototyping. A computer-controlled laser beam induces a phase change in a thin layer of photosensitive liquid. The liquid changes phase – becomes solid by polymerization – where the laser beam hits the surface. A new layer is then built on top of the solidified layer, and the procedure is repeated until the object is finished. Other devices aggregate drops or streams of thermoplastic material to build the model. There were also devices that use laser-cut paper sheets laminated to a block (LOM), but they have been superseded by less expensive techniques with more capabilities, such as the powder-based devices which are used for most applications.

A thin layer of a powder, such as starch, plaster, photopolymer or metal, is deposited onto a building platform. The regions of the layer that are to become part of the model are fixed by selective spraying of an adhesive, by polymerization with an UV light beam, or by local heating with a laser beam (selective laser sintering). When the first layer has been fixed the second layer is deposited, and so on, until the final layer is accomplished. After completion of the model the loose powder is removed by shaking or with the help of an air jet. Most devices allow recycling of the unused material.

Which process or device should be used depends on the purpose for which the prototype is intended. For instance, stereolithography achieves very smooth surfaces, but is expensive. Laser sintering, also called direct metal printing, produces metal parts which are stronger than parts from other processes. The artist Bathsheba Grossman uses direct metal printing to create multiple copies of sculptures based on mathematical concepts (www.bathsheba.com). A combination of starch powder and wax can be used to build a pattern for investment casting. The part is covered with refractory slurry and then the wax is vaporized and replaced by the molten metal. Some powder materials can be finished with tools used for wood and electroplated subsequently to give the appearance of metal.

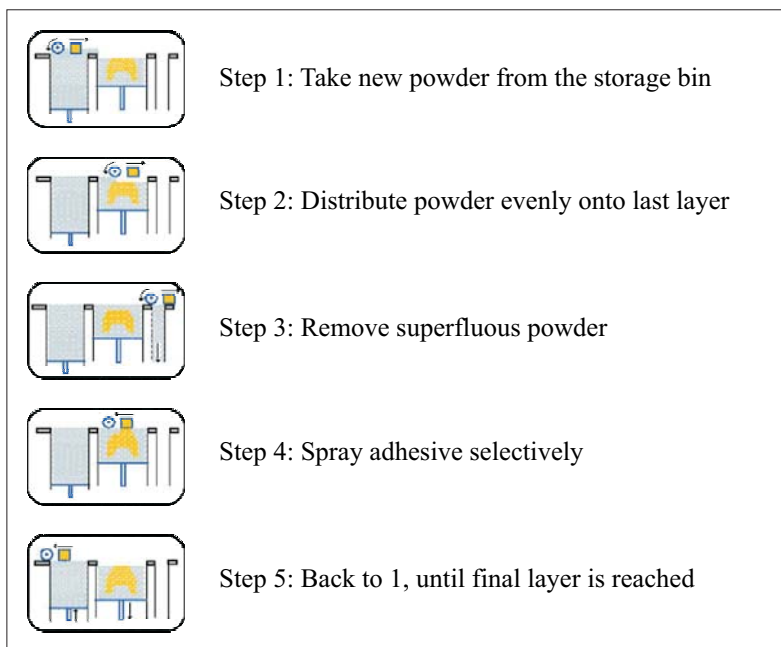


Figure 1: Building steps for 3D printers

Color is an essential graphic variable in cartography and model visualization. Until a few years ago the direct application of color during the buildup stage was not available, and the raw models had to be colored manually. The application of color must be integrated into the building process of the model to keep the production within a reasonable cost frame. In recent years new RP devices were developed which can apply color in high resolution and in many program-controlled shades, which makes it feasible to use the technology to build physical models of buildings, landscapes and other cartographic objects. The rich color spectrum and the use of standard inkjet printer parts probably caused the manufacturers to call their devices 3D printers.

The first 3D printer with integrated high resolution color capability was introduced in 2001 by the company ZCorporation (www.zcorp.com). As well as using transparent adhesive, the device applied three colored adhesives containing pigments of the subtractive base colors cyan, magenta, and yellow. The result is a multi-colored part. The finished model should be infiltrated with a hardening liquid, such as epoxy or cyanoacrylate, to improve the mechanical strength and to protect against high humidity.

The 3D printers of Zcorp are still the only devices on the market that provide multi-colored parts. The most recent addition to the family, the 3D printer Z650, obtained an additional print head with black pigments. The Z650 provides real CMYK colors with a resolution of 600 x 540 dpi. The capability to provide color integrated into the build process opens many new applications for RP aside from cartography and GIS. For instance multi-colored models of molecules, buildings or plants can be produced, and there are many potential uses in medical visualization improving clinicians' comprehension and understanding of data from x-ray or magnetic resonance scanners.

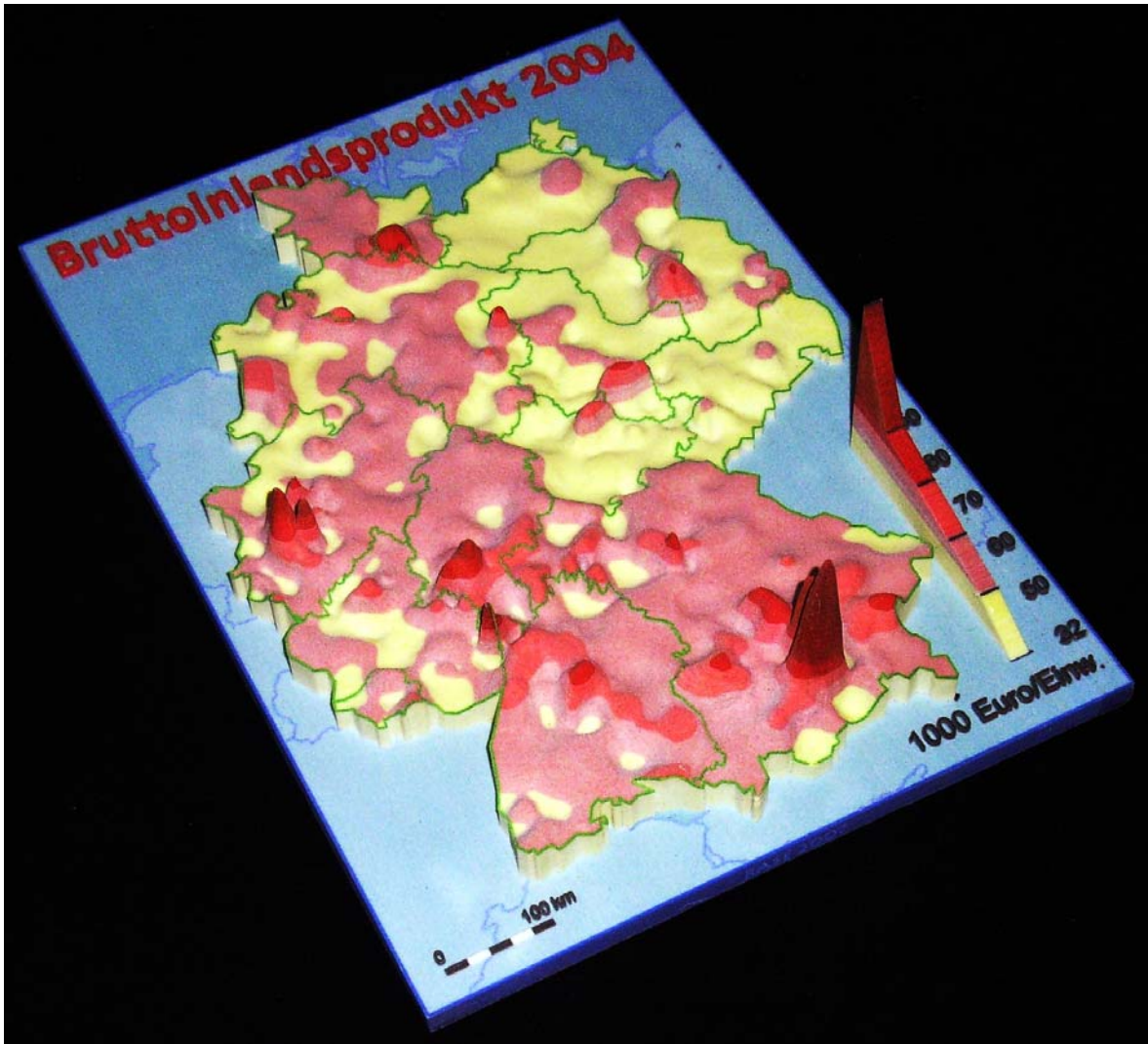


Figure 2: Physical model of an interpolated smooth surface representing the domestic gross product per capita in Germany

The software for the 3D printers slices the numerical representation of the model into layers of user-selectable thickness, in the range 0.089 to 0.102 mm. The thickness of the layer determines the resolution in the z -direction, and hence the production time. A value of 0.1 mm was used for the surface models referenced here. Approximately two colored layers can be built per minute. The Z650 printer can handle parts up to 254 x 382 x 200 mm.

Laser subsurface engraving

Laser subsurface engraving (also known as laser etching) is performed by a computer-controlled device where a focused laser beam melts a tiny spot in a glass block, destroying locally the transparency of the glass. The melting of many spots results in a visible 3D model, which might be a building, a human portrait, or a cartographic surface. The laser beam and its focus are moved in relation to the glass block using data derived from a numerical representation of the object. It is obvious that the melting process has to start with the lowest layer, otherwise the laser beam would be occluded. The equivalent 2D representation is a pen drawing or an etching which is why I like to call this the *Dürer* method. The object inside the glass block is monochrome. Putting it on a pedestal providing adequate illumination is advisable to insure good visibility. Nearly identical VRML files as with the 3D printer were used to generate the surfaces inside the glass block. The files were sent by e-mail to the company which builds the computer-controlled laser engraving devices (www.vitro.de). The manufacturer of the device offers now additional software to its customers, intended to improve the visual appearance of the models in the glass block.

For some time now a franchise organization operates many shops in several countries, providing etching devices and 3D cameras necessary to do 3D portraits on the spot (www.looxis.com). Most of these shops are able to accept 3D files and produce the laser etching for customers.



Figure 3: Glass block with laser-etched 3D surface

Rapid prototyping of 3D city models

Several parameters determine which of the available rapid prototyping methods can be used to produce a 3D model of the city, considering the level of detail, the visual appearance, e. g. the use of color, and the production cost. Table 1 displays a general overview of the different RP methods in relation to the level of detail (LOD) used for city models.

Table 1: Suitability of RP methods for city models (* = possible; ** = better; *** = best)

LOD	0: landscape	1: extruded prisms	2: roof, simple texture	3: details, texture	4: interior
Aggregation, no color; 3D printer, STL, SLS	*	*	*	*	*
Aggregation, with color; 3D color printer	***	***	***	**	**
Removal; CNC milling	*	**	*		
Transform (CNC milling required)	*	**	**	**	
Laser subsurface engraving	*	**	*		

The visual variable color is indispensable for city models, with very rare exceptions. Only 3D printers are able to provide colored models at reasonable cost for single units. Textures on vertical walls, however, are not satisfactory due to the thickness of the layers. If multiples of the same model should be provided it seems feasible to apply an RP technique using transformation by heat and pressure. A model cut by NC machining from a block of high-grade wood or shining metal is a luxury, but not appropriate to the financial situation of most cities. Laser subsurface engraving is a cost-efficient solution to create monochrome 3D representations of buildings and ensembles, comparable to 2D drawings.

Figure 4 shows a part of the model of Vienna, Austria, created by the city of Vienna in cooperation with the company 3dmodell (www.3dmodell.at). The model was produced in several parts on a 3D printer (Z650), and assembled manually on a platform.

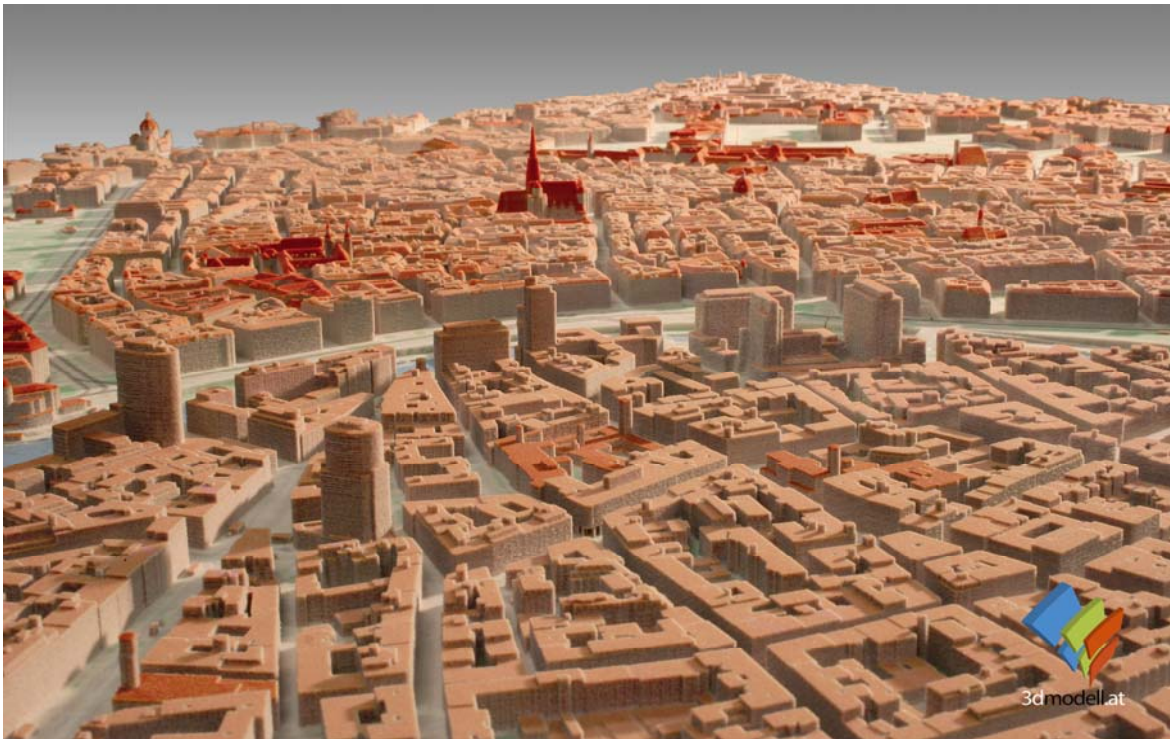


Figure 4: Part of the city model of Vienna, Austria, produced on the 3D printer Z650 in several parts (courtesy of [3Dmodell](http://www.3dmodell.at))

Models of surfaces derived from demographic and socio-economic data

For the visualization of cartographic surfaces generated from demographic, socio-economic or accessibility data some physical models were produced (Fig. 2, 5,6). The continuous surfaces depicted in the models were interpolated from point or polygon data, with the geometric base data prepared using a standard GIS package (ESRI ArcGIS). Interpolation of polygon-based data was performed using the pycnophylactic interpolation method [TOBLER 1979, RASE 2009a, b].

The model – surface, base, legends, text strings – is represented by an irregular triangular mesh which can be stored in different file formats used for 3D models. In our case the VRLM97 or PLY file format were used. Many CAD programs and viewers are available which allow the display of VRML files for visual inspection of the models, including syntactical checks of the triangular mesh.

The boundaries and other lines are represented by thin tubes (Fig. 5). The tubes, the situation and the legends all consist of 3D triangular meshes. The text strings are 3D parts extruded from the TrueType character definitions (glyphs). The form of the extrusion and the bevels can be controlled with several options. The graphic resolution of the glyph is selectable, depending on the character height. Any TrueType font can be used, provided that the syntax of the glyphs is correct, which is not the case for all TrueType files available, as we found out.

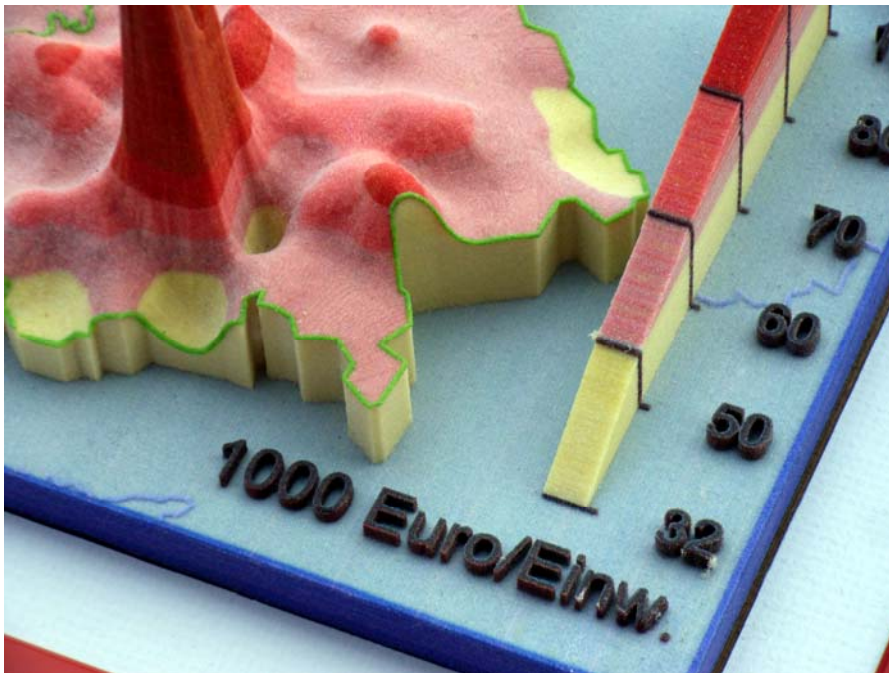


Figure 5: Enlarged part with legend and text

The interpolation and the triangle generation including the meshes representing the tubes, areas, legends and 3D text, are done with our own software. Standard viewers for 3D models are used for simple visual checks of the models. Before the files are transmitted to the 3D printer a thorough check is performed to reveal and correct serious problems which could spoil the build process.

Even though 3D printers now cost less than half as much as a high-quality mechanical 2D plotter did about 20 years ago, it is not economical to buy a 3D printer for only occasional use. It is less expensive to use the services of a contractor to build the models. The VRML files with the model representations were sent to 4Dconcepts (www.4dconcepts.de) as attachments to e-mails. Assuming that no errors are detected during an extra check at the contractor's premises, the model is built on the printer, infiltrated with the stabilizing liquid, and then returned to the customer by a parcel service (RASE 2006).

Figure 6 is a photograph of a model representing a trend surface interpolated from unemployment data. A bivariate LSQ polynomial of order 5 describes the overall spatial trend of unemployment, with high values in East Germany and low values in Southern part of Germany as expected. The representation of the surface is supplemented by columns representing the residual values, the deviation of the actual value at each point from the value of the trend surface. Because the negative value (unemployment less than the trend) cannot be visualized by holes color codes are used to express negative (cyan) or positive (magenta) residuals. In Berlin and the region southeast of Berlin have, for example, the actual values are lower than the trend, and the columns are colored cyan.

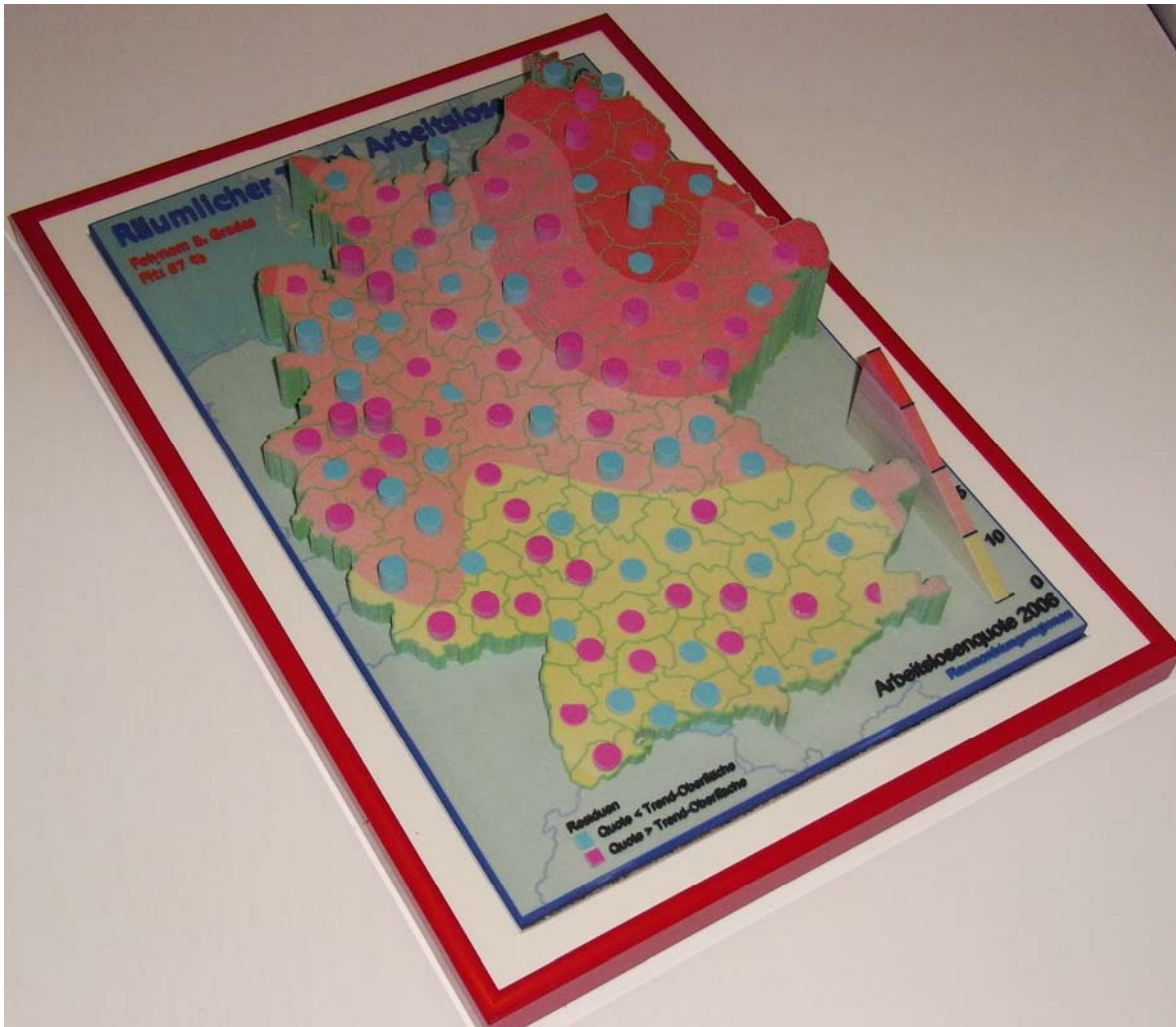


Figure 6: Spatial trend surface (order 5) and color-coded cylinders representing residuals

The model in figure 7 represents the results of accessibility computations for the railway and road network in Germany. The heights of the surface are proportional to the average time distance from selected points in the network to the next central place by using the rail-based traffic system. The travel distances at the selected points serve as the z values the surface is interpolated from. At the points identical with the central places the surface is zero (no travel distance), and the highest values occur at the peripheral regions. Other measures in the accessibility model are the travel distances to railway stations for long-distance travel, airports, or other public services, based on both private and public transport facilities.

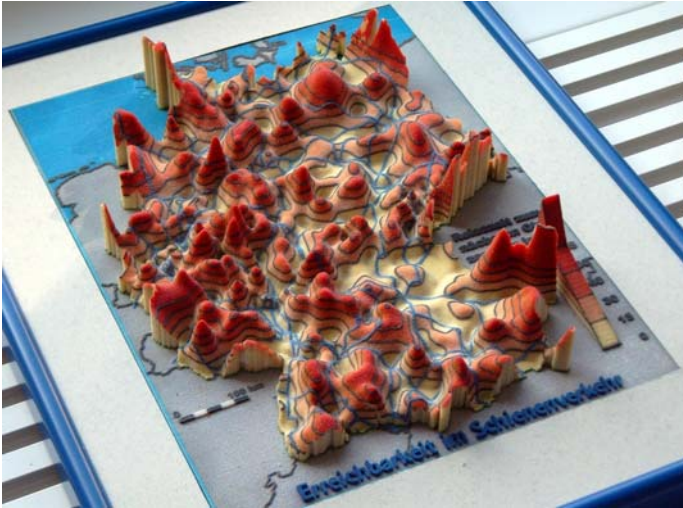


Figure 7: Surface of time distance to the next central place (accessibility)

Relief models with user-selected texture

The most recent addition to the facilities for creating “true” 3D models is the WWW-based service offered by LandPrint (www.landprint.com). After downloading a Java applet the user can select any place on earth by typing a name. The application zooms in to that place, provided the name is stored in the data bank. The user has to define a window on the surface, and a factor for the height value from 1 to 5. The textures overlaid on the relief include satellite images and topographic maps at different scales, at the moment US maps only. It seems that the relief data and the satellite imagery are derived from Google Earth (<http://earth.google.de>).

The customer can also supply a trajectory from a GPS recorder to be displayed on the relief. The GPS paths make the service attractive for outdoor-oriented customers who want to represent on a 3D model their personal routes they took on their roaming, canoeing, biking or geocaching tour. The application of user-supplied geo-tagged imagery is in preparation but not available yet (February 2009). The models can be built in different user-selectable sizes. The company ships the models to the customers by a parcel service, but only within continental USA.

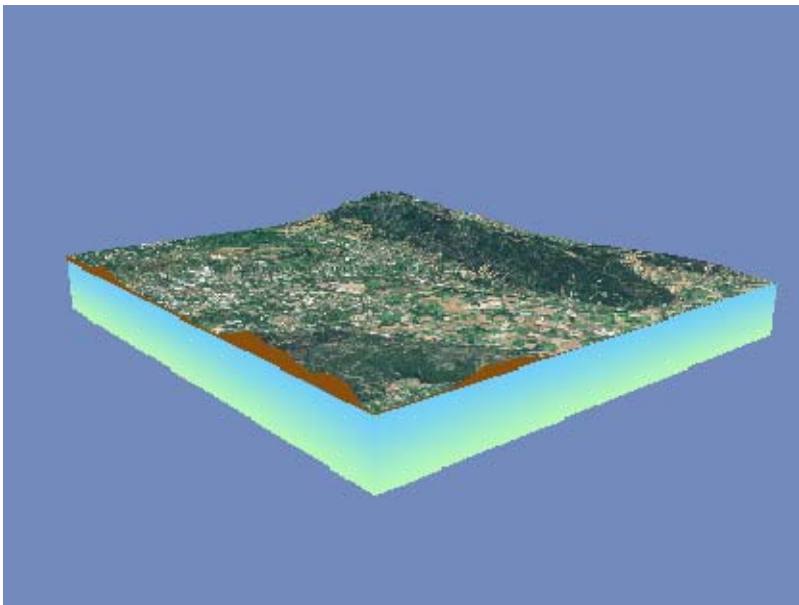


Figure 8: Screenshot of relief model created by LandPrint. Location: Chaîne des Alpilles (rear), city of Saint Rémy-de-Provence, France.

For European customers interested in building relief models in the same way a Danish company has licensed the LandPrint technology including the Java applet (www.3dlandprint.dk). The models are built on a 3D printer Z650. At moment the website is in Danish only, but the firm is planning to provide web pages in English and other languages. The use of European topographic maps is in preparation. The prices for the models are very competitive.

Benefits of physical 3D models

Physical models of GIS objects are unlikely to replace paper maps or virtual reality techniques. However, a model has all the advantages of a perspective drawing or a stereogram. In addition, viewing ambiguities, such as the inversion of the depth impression, a recurrent problem with 2D drawings and sometimes also with stereograms, can be resolved by a minor movement of the head or body.

The estimation of distance and height within the model is easier with a physical model due to the lifelong experience with 3D views. When a group of people are trying to grasp a spatial situation or process a physical model can have advantages over VR methods. VR equipment is still expensive, less transportable than a physical model, and is not usually able to support multiple users. The production of a physical model, to be fair, is not cheap either, although the prices became more affordable recently.

A physical model can be used for representative and promotional purposes, for example on display in the entrance hall or an office, or exhibited at a fair. In this context models have an important job as *conversation pieces*. The technical explanation how the model was built can lead to a discussion of the problem that the model is trying to clarify. This is very important for environments where decision makers have no immediate relationship with spatial science, GIS or cartography. The model is the medium to introduce the message in a roundabout way, a kind of subversive cartography. An illuminated glass block with the etched object inside falls into the same category, as an eye-catcher or conversation piece. It can also serve as a rather inexpensive theme-related trophy or a personalized present.

Something unexpected happened when I showed these models to my colleagues for the first time: nearly everyone spontaneously tried to touch the surface of the model. To touch the material and the surface forms, to use the haptic sense, is obviously a basic desire, equivalent to the desire to use the other senses. Touching is not reserved for people with a visual handicap, although they would certainly benefit from the economic advantage of producing special maps by rapid prototyping techniques.

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