

3D Charts – Taxonomy and Implementation in a Virtual Globe

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Abstract. Charts are key elements in thematic cartography to visualize multivariate data. While taxonomies and construction theories of 2D charts are well-elaborated, a concise framework for classifying and creating 3D charts is still missing. In this paper, we therefore propose a taxonomy for 3D charts which distinguishes between 3D point, line, surface, and solid charts. Special focus is put on the properties of solid charts. Based on these properties and with the aid of open-source software, we create six solid chart maps in a virtual globe which depict spatio-temporal data of the Atlas of Switzerland.

Keywords: Charts, Virtual Globes, 3D Cartography, Atlases

1. Introduction

In the 20th century, cartographers established a variety of chart types for maps. Well-known examples are the pie chart and the bar chart. Charts are composed of geometric primitives (e.g. circle sectors, rectangles) which can be differently scaled, arranged, colored, and optionally labelled. By encoding univariate or multivariate data with those graphical variables, charts help to visualize statistical data, mostly at point locations. Although some 3D chart types, e.g. divided repeated cubes (Imhof 1972), are propagated for printed maps in the last century, they are rather an exceptional case in thematic cartography. This attributes to the fact that charts were used almost exclusively on two-dimensional maps in the last century.

Since the beginning of the 21st century, high-performance computers and advancements in computer graphics fostered the development of 3D cartography. Great progress has been made in creating virtual globes engines, such

as NASA World Wind¹, Google Earth², or Cesium³. Compared to 2D maps, virtual globes have an additional dimension available which can be used as a visual variable to represent thematic or temporal geographic data. Charts can also benefit from this third dimension. According to the concept of the 3D Mapping Space (Sieber et al. 2013), it is desirable to recognize main chart properties from a bird's eye view and gain additional information when tilting the globe.

2. Related work

A comprehensive overview of existing chart taxonomies – e.g. Imhof (1972), Bertin (1974), Hake et al. (2002) – is given in the dissertation of Schnabel (2007). Although these taxonomies partly contain 3D charts, they are designed for 2D maps primarily. Schnabel (2009) suggests an own theory on how to construct charts and provides a markup language for a web application which helps users to generate 2D charts. A more recent classification of 2D charts has been developed by Tsorlini et al. (2015). The classification serves as a decision tree in a wizard which assists the user in creating thematic maps. Based on the input data and following cartographic principles, suitable chart types are recommended by the wizard.

Despite the lack of a 3D chart taxonomy, scientists make use of 3D charts to visualize geographic data in a virtual globe. In his master thesis, Sandvik (2008) represents population data by 3D (hemi)spheres whose volumes are proportional to population counts. Moreover, he scales heights of 3D bars to the number of Internet users in each country. Stacked 3D bars are realized by Lang & Gutiérrez Corea (2010) who therewith illustrate damage probabilities of earthquakes. Each 3D bar represents cumulative damage probabilities of five damage states. Marek et al. (2014) implemented stacked 3D spheres in Google Earth to visualize occurrences of diseases. Spheres are ordered chronologically and connected vertically by a straight line. Sphere size and color represent the number of cases.

¹ <http://worldwind.arc.nasa.gov/java/>

² <https://earth.google.com/>

³ <http://cesiumjs.org/>

3. Existing implementations

Two software products – *ESRI's ArcGlobe* and *Microsoft Excel's Power Map* – have been reviewed for creating 3D charts in a virtual globe. Both products have a graphical user interface allowing the user to select different chart properties:

In *ESRI's ArcGlobe* (Figure 1), 3D bars – either stacked or aligned next to each other – and 3D pie charts are displayed as billboards in the virtual globe. For both chart types, the thickness as well as the color of segments and outlines can be changed. Bar charts can be aligned vertically or horizontally, and the bar width and the space between bars can be defined. Moreover, coordinate axes and leader lines can be added as visual aids. Pie charts in contrast can be orientated arithmetically or geographically, and tilted. Other representations of point data comprise 3D solids (e.g. tetraeders), 3D icons (e.g. cars), and 3D markers (e.g. fonts). These 3D objects can be colored, scaled, or rotated differently. They are inserted into the virtual globe at a fixed position. Next to point data, also 3D lines and polygons – optionally extruded or with a certain offset – can be visualized.

Microsoft's Power Map for Excel (Figure 1) enables creating 3D bars – either stacked or horizontally aligned – and 3D pie charts on a virtual globe surface. Numeric values in the underlying data table define bar heights and angles of pie segments as well as the pie radius. Categorical values lead to uniquely colored charts. Segment colors, chart opacity, and a factor for horizontal and vertical scaling can be set for both chart types. Additionally, five different shapes can be selected for bar charts. All parameter modifications are immediately visible in the globe. Beyond that, charts are animated initially: 3D bars grow from the ground into the air and 3D pies grow from their midpoint. When being selected, chart segments are highlighted and the underlying data values are shown.

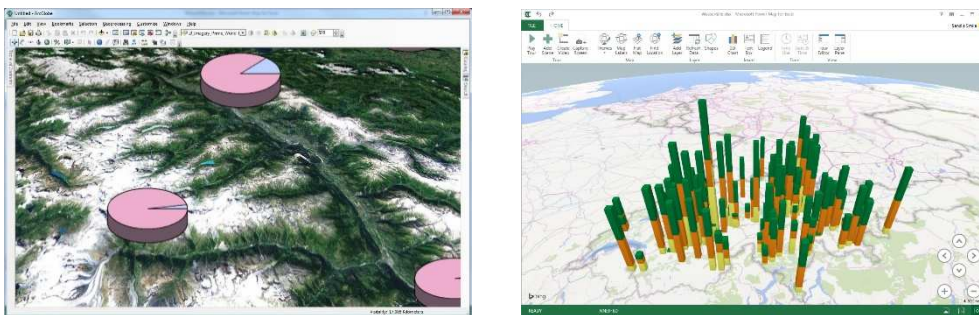


Figure 1. 3D pie charts in *ESRI's ArcGlobe* (left) and stacked 3D bar charts in *Microsoft's Power Map for Excel* (right).

The analysis of these two software products shows that it is already possible to create 3D charts in a virtual globe. From a cartographic point of view however, the number of different chart types and customization possibilities is rather small. Also, the potential for representing data by including the third dimension is not fully tapped. The following taxonomy shall help to reveal further examples and properties of 3D chart types.

4. Taxonomy

The proposed taxonomy classifies charts according to their base geometry into 3D point, line, surface, and solid charts.

4.1. 3D point charts

Dots can be placed in or on 3D objects or in the 3D space to represent attribute values. Additionally, values can be encoded by dot size and color.

In the *3D dot scatter chart* or 3D scatter plot (*Figure 2*), point positions are determined by the distance to the x-, y- and z-axis. Axes are perpendicular to each other and values are proportional to distances on the axes. With the 3D dot scatter chart, it is possible for instance to identify point clusters.

In the *3D dot density map* or point cloud map (Sieber et al. 2013), each dot represents a certain value. Dots are scattered randomly within polygonal map areas and are translated in z-direction in case the distance between two points has fallen below a certain threshold. Peaks indicate a large density.

As special 3D point charts, two 3D counterparts of the 2D triangular chart are imaginable: In a *triangular prism*, a fourth variable could be introduced and represented on an axis which is orthogonal to the other three axes. In a *tetrahedron*, dots could be placed on three faces so that three of four variables can be compared on a face at once. The bottom face of the tetrahedron is likely not to be used.

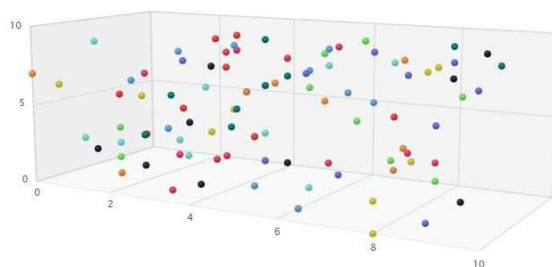


Figure 2. 3D dot scatter chart (<http://www.highcharts.com/demo/3d-scatter-draggable>).

4.2. 3D line charts

One or more lines can be drawn in the coordinate system or on the faces of a three-dimensional object (e.g. a cube). Lines interconnect points whose distances to the axes are proportional to the values they represent. Interpolated values can then be read on the line. To distinguish between multiple lines, line width, color, and dash pattern can be changed.

Line segments can be *extruded* and stacked vertically in chronological order (Tominski et al. 2012). The resulting bands enable visualizing attribute values on them. This allows for instance exploring trajectory data of moving objects, e.g. velocities of cars (Figure 3).

A 3D equivalent of the *radar chart* or Kiviat chart is also thinkable. An additional variable, e.g. time (Figure 3), can be depicted on an axis which is perpendicular to and in the center of the radar axes. Areas of the 3D radar chart can be filled out optionally, as done by Hackstadt & Malony (1995).

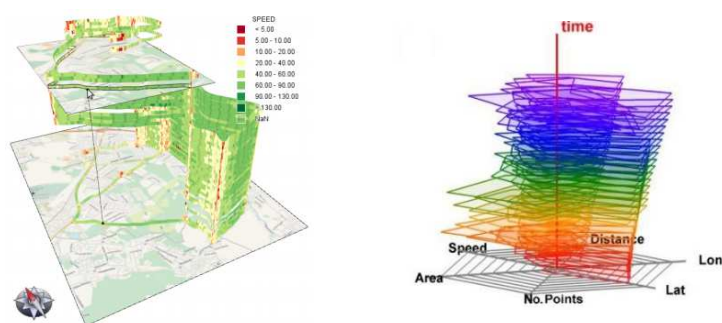


Figure 3. Stacked extruded line segments (left; Tominski et al. 2012) and 3D radar chart (right; Peters 2014).

4.3. 3D surface charts

3D Surfaces are arbitrarily curved planes in the three-dimensional space. They help to visualize continuous areal phenomena, e.g. annual precipitation⁴. Surface cells can be color-coded and a graticule can be drawn on the surface as a visual aid.

Vertices of 3D surfaces can be connected to the ground to build up *3D areas* (Figure 3). Multiple 3D areas can be arranged side by side to prevent an overlap. They can be also cumulated to form *stacked 3D areas*. This facilitates

⁴ <http://goworldwind.org/demos/> – Analytic Surface

comparing values of different 3D areas and finding maxima and minima of value sums.

All mentioned 3D surface chart types are available in the spreadsheet program Microsoft Excel 2013.

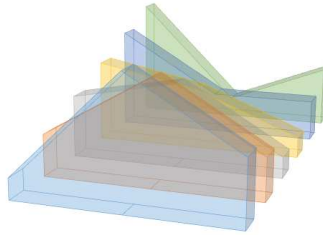


Figure 4. 3D area chart created with Microsoft Excel 2013.

4.4. 3D solid charts

Solids are polyhedrons with flat faces which can be inserted into the 3D space to construct charts. The properties of 3D solid charts (*Figure 5*) are explained in the following:

4.4.1. Shape

A solid chart usually consists of one base shape type. 3D cubes, cuboids, and spheres appear for example in Schnabel's dissertation (2007). Also thinkable are extruded 2D shapes, like cylinders and prisms (e.g. hexagonal prisms), as well as real 3D shapes, such as platonic solids (e.g. tetrahedrons), star polyhedra, cones, tori, and frustums. In general, regular polyhedrons are taken for a better comparability. Irregular, deformed (e.g. twisted, sheared) solids are rather the exception.

4.4.2. Scale

The size of solids can be altered to express numerical values. Values can be proportional to the side length, the face area, or the volume of a solid. The scaling direction can be along a straight line (linear scaling), around an angle (polar scaling), or arbitrary. An example of arbitrary scaling would be to carve a little solid out of a larger solid.

4.4.3. Rotation

Solids can be rotated along their x-, y-, and z-axis. Thereby, the focus can be put on other properties when viewing the solid from a different viewing perspective. For example, an upright cylinder looks like a circle from the top and like a square when the cylinder is rotated 90° around its x- or y-axis.

4.4.4. Segmentation

Solids can be subdivided into different segments, whereat each segment represents a certain proportion of a whole. Common subdivisions are straight line sectors, circle sectors, or rectangle sectors. Examples of a sphere with circle sectors and a cuboid with rectangle sectors can be found in Schnabel's dissertation (2007).

4.4.5. Repetition

Solids can be repeated several times and values (e.g. counts) can be proportional to the number of repetitions. The divided repeated cubes chart (Imhof 1972) illustrates this property.

4.4.6. Composition

It is possible to create a solid chart consisting of different shapes. For example, a coin chart may combine squares and circles to represent population counts (Imhof 1966). Each shape symbolizes a certain number of residents, whereat total counts can be derived by the sum of values.

4.4.7. Alignment

Chart components, i.e. solids or segments, can be arranged in different ways, for instance along a straight line, in a grid, or along a spiral line. Additionally, a gap can be inserted between chart components, at which the size of the gap may be proportional to certain values (e.g. time). Furthermore, chart components can be sorted by their underlying values in ascending or descending order. Other alignment properties comprise the starting point (e.g. bottom vs. top for vertical alignment, 0° vs. 45° for circular alignment) and the anchor points of chart components (e.g. center, bottom-left, etc.). The spinning direction (clockwise, anti-clockwise) can be defined for circular alignments.

4.4.8. Surface properties

Solid faces can vary in color, transparency, reflectivity (diffuse, specular), and shading (flat, phong, etc.). Different patterns, textures, gradients, or even little bumps can be applied to the surfaces. The surface color is predestined to be used as a visual variable.

4.4.9. Outline properties

Outlines help to distinguish between the different chart components. They can differ in color, transparency, width, dash pattern, and line join.

4.4.10. Visual aids

As sizes are difficult to compare in 3D space, a reference grid or the outline of the solid representing the maximum value may be added to solid charts as visual aids. Also, labels with chart values or names can be attached. Different anchoring techniques (e.g. leader lines, cast shadows) can be applied to preserve the relationship between the solid chart and its corresponding position on the ground.

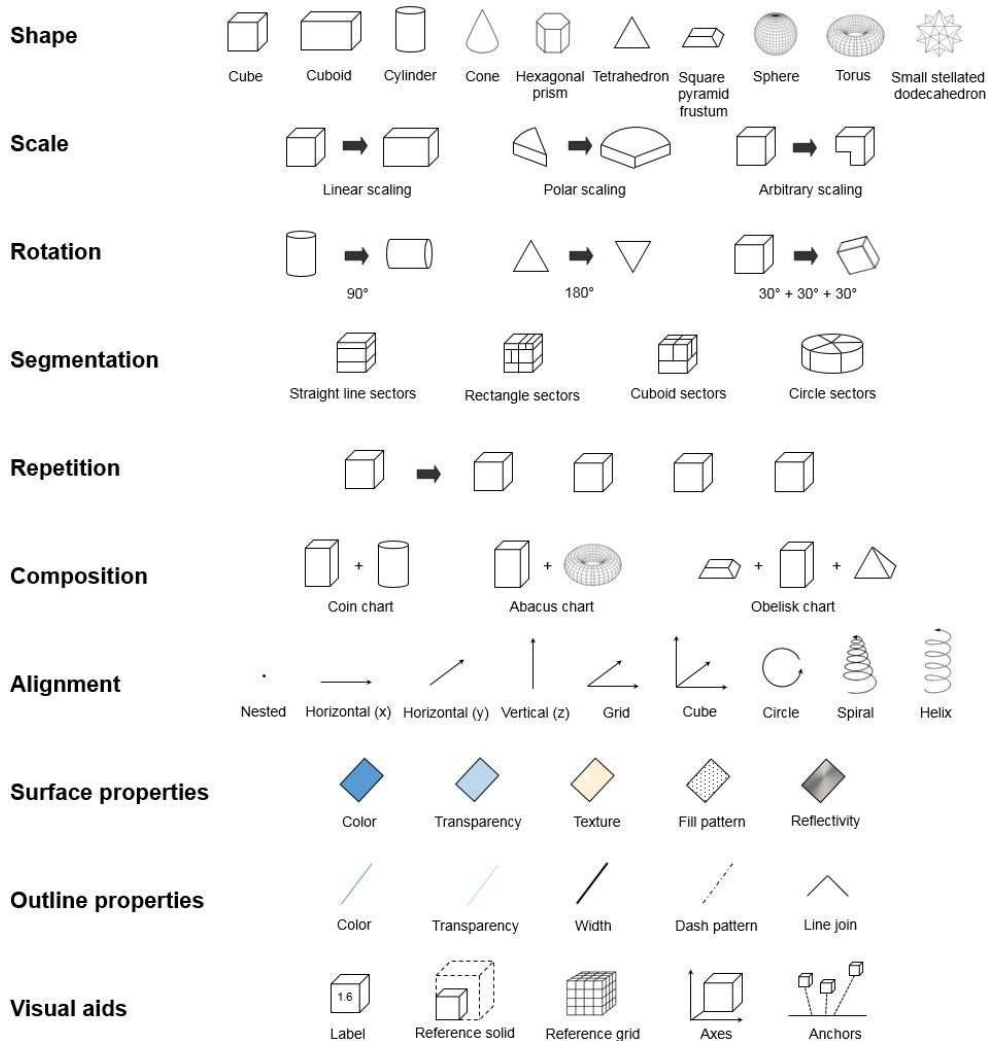


Figure 5. Properties of 3D solid charts at a glance.

5. Implementation in a Virtual Globe

Six maps with different types of solid charts have been created in a virtual globe. This section describes which data and tools were used to implement them, it explains the properties of the resulting charts, and it suggests how the charts can be further improved.

5.1. Sample data

The test data originates from the Atlas of Switzerland, which is the national atlas of Switzerland. The atlas contains multivariate data from various domains and thus serves as an ideal test bed for implementing 3D charts. The exemplary data sets are taken from the domains of nature and environment, and society. These thematic data are stored in database tables which are associated with point geometries. Topographic background data comprise a grey-scale and a colored shaded relief, water bodies, and a satellite image.

5.2. Workflow

Charts are constructed by applying transformations (translation, rotation, scale), CSG operations (union, intersection, difference), and colors to geometric primitives in *OpenJSCAD*⁵, a JavaScript-based CAD software. Attribute values in the sample data sets, which are traversed iteratively, and a configuration file in JavaScript determine the type of operation to be performed. 3D charts are exported in the X3D data format, which does not only allow to store geometries, but also graphical attributes (e.g. diffuse color).

Next, X3D documents are imported in Blender⁶, a 3D modeling software, with a Python script. The operation “Limited Dissolve” converts triangles with shared edges and normals into polygons, so that outlines of charts can be added later on. After this, model coordinates of polygons are transformed into a projected coordinate system. Chart polygons are finally exported in GeoJSON format, which has the advantage that also attribute data can be included for feature queries.

The command-line tool *ogr2ogr*⁷ then transforms the chart polygons from the projected to the WGS-84 reference system. The resulting GeoJSON document is loaded and displayed in *osgEarth*⁸, a C++ based virtual globe en-

⁵ <http://openjscad.org/>

⁶ <http://www.blender.org/>

⁷ <http://www.gdal.org/ogr2ogr.html>

⁸ <http://osgearth.org/>

gine. In case the GeoJSON is too large (> 10MB), it is split in several tiles with the osgearth_tfs application.

5.3. Results

5.3.1. Stacked cuboids

Length, width, and height of cuboids can be scaled proportionally to numeric attributes of a feature. In this chart example (*Figure 6*), length and width represent areas of glacier surfaces. Together with a calculated average height, cuboids depict glacier volumes. Cuboids are stacked on top of each other having their anchor-point at the top-left corner. Varying shades of blue have been used for different years of measurement. A decline of volumes is apparent for glaciers in this extent.

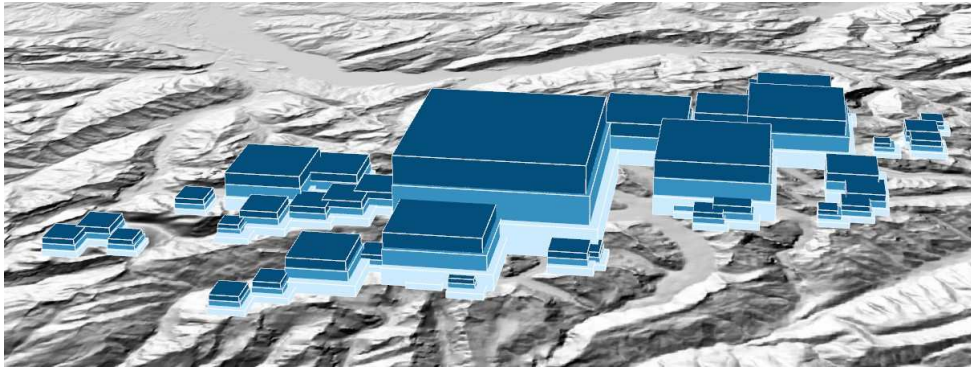


Figure 6. Stacked cuboids: Volumes of glaciers in Switzerland measured in years 1850, 1978, and 1998 (from bottom to top).

5.3.2. Stacked pyramid frustums

In contrast to the stacked cuboids (*Section 5.3.1*), this solid chart (*Figure 7*) is based on square pyramid frustums which are separated by a small gap. The area of the frustum represents population counts of different years which are shaded in greenish hues. The most recent census is visible from the top. Development trends – increases, declines, and stagnations – can be inferred from the slope of the frustum.

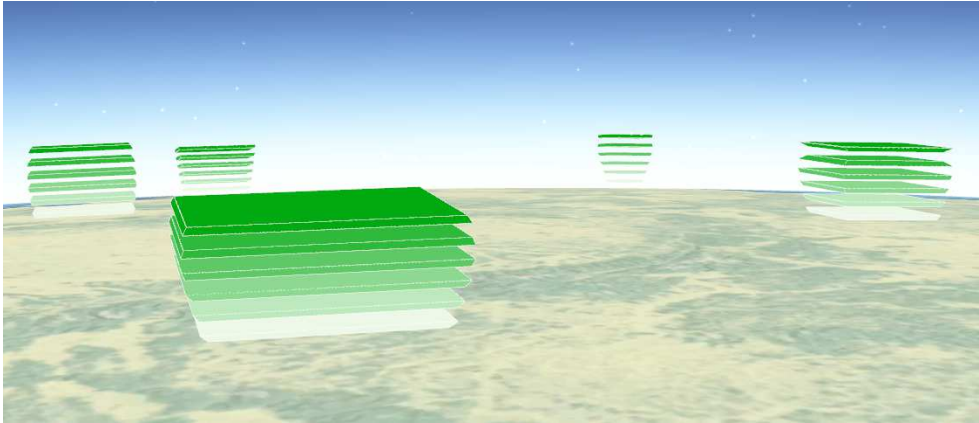


Figure 7. Stacked pyramid frustums: Resident population in different European countries in years 1960, 1970, 1980, 1990, 2000, and 2010 (from bottom to top).

5.3.3. 3D coin chart

This map (*Figure 8*) is composed of different shapes, i.e. segmented cylinders and cuboids. Shapes (= coins) represent a fixed number of people living in a certain circumference. Solids are placed in cells with a high population density and filled up eventually with values from neighboring cells. The map is based on a population distribution map from the printed version of the Atlas of Switzerland (Imhof 1966). This 3D version depicts different age groups on the height axis and includes population counts of the last census in Switzerland, which took place in year 2000.

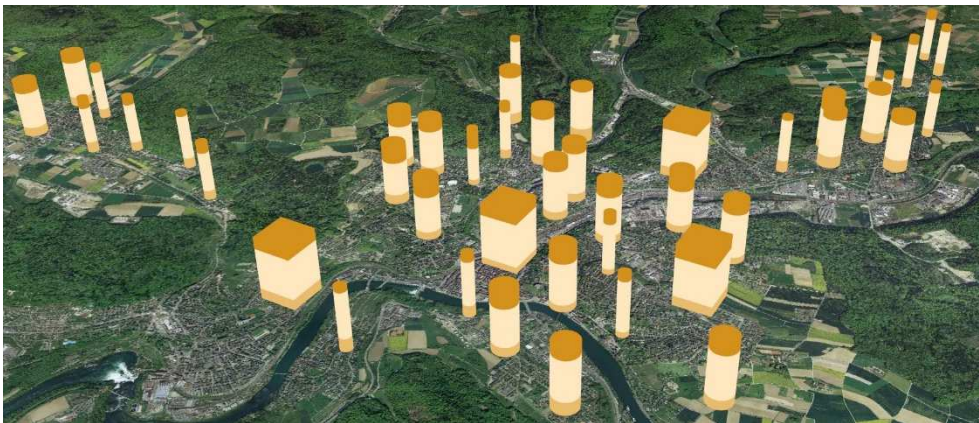


Figure 8. 3D coin chart: Distribution of people aged 0-14, 15-64, 65 years and older (from bottom to top) in the city of Schaffhausen. Cuboids represent 5000 inhabitants, bigger cylinders 1000, and smaller cylinders 200.

5.3.4. Nested hemispheres

In this example (*Figure 9*), hemispheres are arranged circularly for the four seasons and nested for 20-year time periods. Diameters of hemispheres are scaled proportionally to the discharge of the river. From a bird's eye perspective, the time period of the maximum runoff is observable and comparable for each season. From an oblique view, runoff variances and individual patterns – increasing, declining, or mixed – can be noticed. Measurement stations are shown as small rotated pyramids.

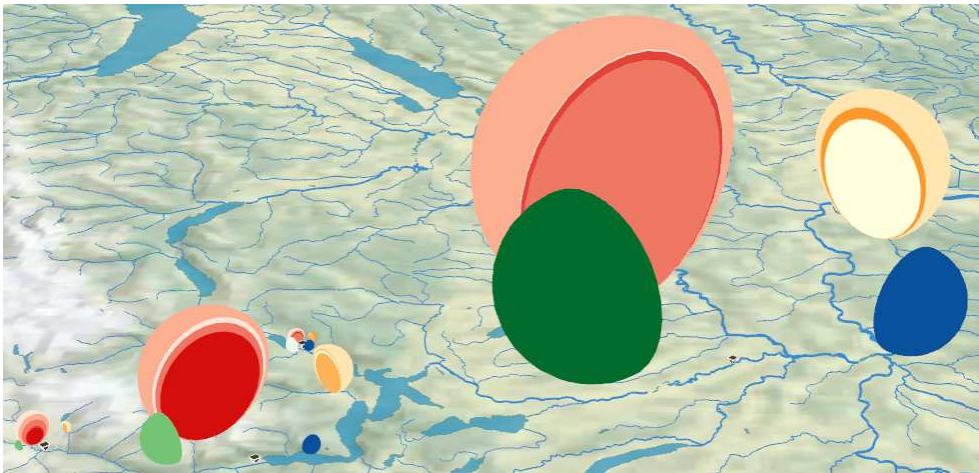


Figure 9. Nested hemispheres: Average runoffs of the River Reuss in spring (green), summer (red), autumn (yellow), and winter (blue) in 20-year time periods in the 20th century. Darker color hues represent more recent time periods.

5.3.5. Helix chart

This 3D chart (*Figure 10*) aligns square pyramid frustums in a helix structure. Each twist represents a decade, each frustum represents a month. Edge lengths of pyramid frustums are proportional to the average monthly runoffs. When viewing the chart from the side, runoffs can be compared for each month in a decade. When viewing the chart from the top, runoffs at different measurement stations can be interrelated by inspecting the radius of the helices.



Figure 10. Helix chart: Average monthly runoffs of the River Reuss in different decades of the 20th century. The most recent decade is at the top of the helix; later decades wind downwards chronologically. Different color hues were applied for months of spring (greenish), summer (reddish), autumn (yellowish), and winter (blueish).

5.3.6. Abacus chart

The Abacus chart is composed of a pole in the middle and multiple tori around the pole. In the example (*Figure 11*), the pole is built of stacked cylinders whose radii are proportional to the sum of colored segment values. For a better comparability of segments from the side, grey segments have been inserted which sum up to the maximum proportion. A small gap separates thematic segments from each other.

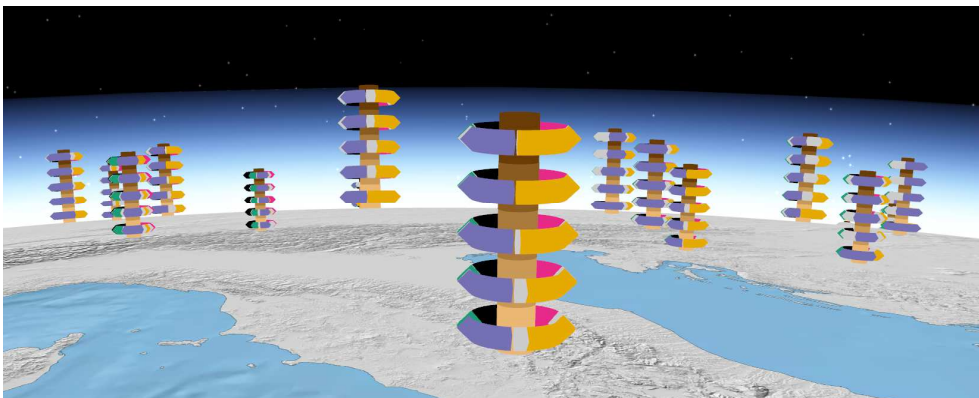


Figure 11. Abacus chart: CO₂ emissions in total (brown cylinders) and per sector (traffic = pink, energy = orange, industry = violet, agriculture = green, others = black) of different European countries from 1990 to 2010 in steps of five years (from bottom to top).

5.4. Future work

While implementing these 3D chart types, six areas have been identified which need further investigation:

Client-side rendering: In the described workflow, chart geometries are generated on a server. Client-side rendering would decrease the amount of data transferred to the client and lead to a more dynamic symbolization. However, more computations would have to be performed on the client to create the charts. Charts would have to be exactly mathematically modelled as CSG operations are quite computationally intensive.

Outline rendering: When viewing a chart with a constant outline width from a larger distance, the outline hides other chart properties (e.g. surface color). An outline width which is scaled to the viewing distance could prevent this effect. Beyond, the outline of a chart might differ from its geometric model. Showing the geometric outline of a cylinder for example would be quite distracting as cylinders are extruded regular polygons and thus consist of multiple sides.

Lighting: Solid charts could be illuminated by a light which is placed at the position of the camera in the virtual globe. The light source then casts shadows on the charts which would help to distinguish different solid faces. Illumination in the form of camera-light or sunlight is already applied to 3D models (e.g. stored in COLLADA format) in virtual globes, however usually not to 3D feature data (e.g. in GeoJSON format).

Interactions: Clicking or hovering a chart component could trigger certain actions. For instance, other chart components might become more transparent, a tool-tip with the corresponding value could be shown, or the active chart part could be translated from the others.

Animations: Animations could lead to a nicer user experience when charts appear or vanish. If the user interface allows modifying filter criteria (e.g. time), smooth transitions could reflect the change of values. In case shapes of solids have to be altered, charts could be morphed into each other.

Usability testing: Future usability studies could reveal whether map readers are able to answer questions more effectively and efficiently with 3D charts compared to 2D charts. Tests could for example examine the comparability of values within one chart or between multiple charts.

6. Conclusion

The shortage of related work and the limited capabilities of existing software products demonstrate that implementations of 3D charts in virtual globes are still in the fledgling stages. By providing a taxonomy, this paper offers a first conceptual framework for constructing 3D charts, especially 3D solid charts. The proposed taxonomy shall not only support map editors in creating 3D charts, but also software engineers in developing markup languages and user interfaces.

The suggested workflow shows that it takes only little effort to generate 3D charts. The implemented 3D chart types are intended to inspire cartographers and to provide attractive but at the same time still readable maps for experts and the general public. 3D charts offer a large potential to catch the interest of the map reader so that he or she can “dive” into the 3D space and find out correlations which would not be that obvious as on a 2D map. By tackling the subjects of future work, the dissemination and usability of 3D charts will be further increased.

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