Temporal GISes of changing administrative boundaries: European comparisons

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This talk looks a variety of approaches to creating GIS databases of changing administrative boundaries. To do so it draws on several European examples to try to show the advantages and disadvantages of a variety of different approaches. We then briefly look at some of the advantages of creating GIS databases of this type.

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Most European countries have been collecting and publishing data about their populations for two centuries or more. A frequently used format publishes data as aggregates of the people living in clearly defined administrative units. The best known example of this type of dataset is the census, however, there are a variety of other sources that also often use this format, for example, to report on the numbers of births, marriages, and deaths, or to report on the number of people receiving Poor Relief or some other form of welfare payment. The structure of these data mean that they are inherently geographical. Recently, the advantages of using GIS to explore these types of data have been demonstrated. The structure of the data is well suited to GIS as the administrative units can be conveniently and accurately represented by polygons, while the statistical data forms attribute data.

In addition to being geographical, these data are also inherently temporal. Many countries publish their census every ten years and other datasets may be published at more regular intervals such as annually. The complexity of the data has traditionally meant that researchers have not been able to adequately analyse data as they change though time **and** space. Researchers looking at single points in time have been able to examine the spatial and attribute components of the data at the maximum level of detail that the data have been published using. When trying to look at change over time, however, the administrative units used have frequently been affected by boundary changes. The traditional solution to this has been to aggregate the data to a higher level which is assumed not to have been affected by boundary changes. In nineteenth century England & Wales, for example, researchers have often aggregated from 630 Registration Districts to around 55 counties. This causes enormous problems: not only is the vast majority of the spatial statistical detail lost, the resulting data will be influenced by the Modifiable Areal Unit Problem to such an extent that the results of many statistical operations such as correlation and regression type analyses will become unreliable.

Traditionally, therefore, there has been a trade-off in exploring these types of data: spatial detail is only available for individual snapshots, while temporal exploration grossly simplifies space.

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GIS should provide solutions to this paradox. It is commonly recognised within the GIS community that the best way to explore, analyse and visualise statistical data within GIS is to use the maximum amount of detail possible or, in other words, to avoid simplification. In the context of datasets such as the census this means preserving the attribute, spatial, and temporal components of the data. Doing this is not as easy as it may first appear. The basic reason for this is that the topological data structure used by GIS to model polygons cannot cope with polygon boundaries changing over time. While software vendors may talk about adding temporal functionality to their packages, research into spatio-temporal data structures has yet to demonstrate an elegant solution to modelling time as it affects polygonal socio-economic data. This means, therefore, that for the foreseeable future researchers wanting to make maximum use of census and similar datasets through the use of GIS must develop their own ad hoc solutions to the problems of change over time.

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The majority of this paper will focus on the different approaches that have been used in Europe to create temporal GIS databases of changing administrative units. It is well documented in the GIS literature that database creation is the most time consuming aspect of most GIS projects. It is also well known among people that have actually tried to build them that it is the most frustrating. Once built, however, these databases offer enormously valuable resources to the wider community, and we have only begun to scratch the surface of the potential for these systems.

There are basically three approaches that have been used or proposed in Europe for the construction of GIS databases of this type: the key dates approach has been used in Ireland and Prussia, the date-stamping approach used by the GBHGIS project, and the space-time composite approach has been used in Sweden and Belgium and is proposed for the Palatinate region of Germany and for a more comprehensive system for Ireland. These three approaches will now be dealt with in more detail.

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The simplest approach can be referred to as the key dates approach. In this, boundaries from important dates or convenient maps are digitised. Attribute data from one or more sources is then linked to the resulting boundaries on the assumption that these boundaries provide a realistic representation of the boundaries used to publish the data even if they are not entirely accurate to the precise day or even year. This approach was used by Kennedy *et al* (2000) to produce their atlas of the Great Irish Famine and is being worked on by Winnige to produce a historical atlas of Prussia. The advantages of this approach are that:

1. it is technically simple,
2. that it does not require detailed boundary change research,
3. that it produces easy project management with clear project deliverables at each stage,
4. and that it is easily extensible in that new dates can be added as required or as funding becomes available. It can also be used as a first step in producing the more sophisticated products described below.

There are, however, several disadvantages:

1. it does not produce a continuous record of boundary change. It merely consists of snapshot maps from various dates,
2. the boundaries it stores may not necessarily be accurate as the maps they were digitised from may be for different dates to the date on which the attribute data were published,
3. there is the potential for massive duplication in terms of both work and storage as boundaries tat do not change may be digitised and stored many times,
4. as the data are digitised from many different sources there is a real danger of sliver polygons if there is a need to overlay data from one date with another. While sliver polygons may seem like a trivial problem, they can in fact cause major problems to analytical work.

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A second approach is what can be termed date stamping. The example shown on the slide shows the area around the Registration District of Bromyard in Herefordshire in the west of England. Through the nineteenth century this was affected by three boundary changes: on Christmas Day 1858 part of its territory was transferred to the neighbouring district of Leominster. On the first of July 1895 a large area was transferred to the district of Martley and two years later a much smaller area was also transferred to Martley. These two later changes also affected the county boundary between Herefordshire and Worcestershire shown in bold.

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This slide shows a simplified representation of the structure that the GBHGIS uses to store this information. ArcInfo is used as in this package it is very easy to manipulate the underlying topological data model. ArcInfo stores information about polygons using a combination of arcs, lines that represent the polygon boundaries, and label points, marked as crosses on the slide, that are used to store attributes about the polygon itself. The GBHGIS stores its data in what are termed *master coverages* that consist of arcs and label points but that have no topology and thus are not converted into polygons. Information about boundary changes are stored as arc attributes. We store information about which county the arc is in (which can be two if the arc is on a county boundary). We also store information about whether the arc is a county boundary or not, and we store information about when the boundary was created and abolished. If the arc was in existence at the start of our period it is given a start date of 0/0/0000, if it was in existence at the end it has an end date of 0/0/5000. The example shows how the boundary change on Christmas Day is stored. Label points store similar information but also include a place name. If an administrative area is created or abolished over the period this is handled by date stamping its label point. Custom written code is then used to extract the arcs and label points in existence at a user specified date and these are then turned into polygons.

The advantages of this approach are:

1. that it provides a continuous record of boundary change,
2. that it has minimal redundancy as each feature is only stored once,
3. and that it can provide the boundaries to the administrative units in existence at any date.

The major disadvantage to the system is that it has no spatial or temporal topology. This has implications for both error trapping and ensuring topological integrity. The system has also been criticised for being overly dependant on a single commercial software package: ArcInfo. This undoubtedly has disadvantages although whether more portable solutions that require far more custom-written software maintained by key staff are any better is open to question.

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The final alternative is what Langran (1992) terms the space-time composite approach. The basic idea of this is to create the administrative units at any date by aggregating smaller polygons together. The *master coverages* in this structure are, therefore, polygon layers with attached attribute tables that contains sufficient information to allow the polygons to be aggregated to form the administrative unit. The *master coverage* can thus be referred to as storing a Lowest Common Geometry. The slide shows an example of how this can be implemented for the area around Bromyard. The Lowest Common Geometry consists of polygon fragments that have either been transferred during the period, such as polygon 2 which the attribute table tells us was transferred from Bromyard to Leominster at time T2, or that have remained in a single administrative unit all the way through, such as polygon 3. A user can the specify the date of interest and the system is designed to aggregate the Lowest Common Geometry to form the appropriate administrative units. Variants on this theme have been used in Sweden and Belgium and are proposed for the Palatinate and to extend the system for Ireland. The Lowest Common Geometry can either be formed by overlaying boundaries at different dates, as in the case of the Palatinate, or from a low-level administrative unit that is assumed to have stable boundaries, as is the case in Sweden.

This approach has all of the advantages of the key-dates approach. It also has spatial and, to an extent, temporal topology. A disadvantage may be that the sheer number of columns needed to stored complex changes over, for example, two centuries may be unwieldy.

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So, bearing in mind the time and complexity of building these systems, why should they be built. Well a basic but perhaps under-appreciated reason is that it allows us to simply produce thematic maps of the data. The slide shows a choropleth map of infant mortality extracted from the GBHGIS. The boundaries are for the administrative units used to publish the data. The pattern shows that the high rates of infant mortality, shaded red, are found in the urban and industrial areas, while rural areas tend to have low rates. The important thing about maps like this is that they present both an overall pattern and also detail that lets us see exceptions. For example, this map shows three parts of Cornwall in the extreme south west that have quite high rates, Norfolk in East Anglia also has unexpectedly high rates.

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Geographers have long known that choropleth mapping may be misleading. GIS opens up the possibility of incorporating more sophisticated visualisation techniques. On this slide, the map on the left is the same choropleth as before. On the right, however, is a cartogram representation of the same pattern. In the cartogram the administrative areas have been distorted according to their population sizes. This shows that although the high rates of infant mortality are only found in relatively few areas, they affect a large proportion of the population. Similarly, the low rates affect far fewer people than the choropleth implies. In fact, the shading scheme used puts 20% of the population in each class.

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A final advantage that GIS offers is the ability to examine change over time. This map also shows infant mortality but in this case for the 1990s. The data have, however, been re-districted such that even though they are 1990s data they are presented on an 1890s geography. This allows direct comparisons over time. The overall pattern is of massive decline in infant mortality from a mean 1890s registration district rate of 127 deaths per 1,000 in the 1890s to less than 4 in the 1990s. The shading scheme used on the slide is again relative and it is apparent that the pattern has changed significantly. Rather than the clear urban/rural pattern shown in the 1890s, modern infant mortality has a much more geographically complex pattern. Because the data have been re-districted onto the same geography, it is possible to directly compare areas. For example, the three districts on the tip of Cornwall have, if anything, worsened their relative positions over time, however, coalfield areas of south Wales that were particularly bad in the 1890s have experienced a relative improvement while other areas to the north of these have become far worse relatively.

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In conclusion, there are three main approaches that have been used in Europe to create temporal GISes of changing administrative units. Of these, the key dates approach is the simplest and easiest to build but provides a good starting point towards the others. It is difficult to say whether the key dates approach is better or worse than the space-time composite. The space-time composite is more theoretically elegant but the answer will depend on the exact nature of the problem and the exact manner in which the solution is implemented. Building these systems is costly and time consuming and this should not be under-estimated. Once built, however, they represent a hugely significant resource. The next challenge is how to use these resources properly to gain maximum knowledge from the wealth of data that they contain. This will also take many years.