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HIERARCHICAL SPATIAL REASONING APPLIED TO THE AUTOMATED DESIGN OF ADMINISTRATIVE BOUNDARIES USING GIS

Abstract: Throughout history, humankind has segmented and delineated the geospatial environment in various ways to support administrative, political and economic activities. To date, the majority of spatial boundaries have been constructed in an uncoordinated manner with individual organisations generating individual boundaries to meet individual needs. This practice has resulted in boundary layers that even the most sophisticated GIS (Geographic Information System) technology is unable to cross analyse accurately. Consequently, geospatial information is fragmented over a series of boundary units.

The objective of this paper is to investigate new methods for the organisation of spatial data by applying the principles of Hierarchical Spatial Reasoning (HSR), where HSR can be used as the theoretical framework for investigating the hierarchical structuring of space and for providing new methods for accurate data exchange. Also, to present the issues found in the development of a prototype developed for delineating boundaries within the GIS environment. This prototype has been constructed utilising the state of Victoria, Australia as a working laboratory for development and analysis.

Keywords

Geographic Information System (GIS), Spatial Units, Data Exchange, Hierarchical Spatial Reasoning (HSR), Spatial Data Infrastructure (SDI)

1 INTRODUCTION

Spatial Data Infrastructure (SDI) is an initiative intended to create an environment which enables a wide variety of users access to complete and consistent data sets in an easy and secure way. SDI comprises policy, fundamental datasets, technical standards, accesses networks and people, it's nature is both dynamic and complex (Rajabifard *et al.* 2000). Increasingly, to support SDI policy, GIS technology is utilised for the storage, display and analysis of geospatial information. This trend has been widely supported by users of spatial information, as GIS provides an array of analytical tools to facilitate the decision making process. However, even the most sophisticated GIS is unable to integrate data sources based on incompatible spatial units. An illustration of this problem in Australia is the extensive use of Australian Bureau of Statistics (ABS) data by organisations and agencies that adopt spatial units different to the ones established by ABS. An accurate extrapolation of ABS data into the boundaries (often postcodes) adopted by other organisations is impossible and requires the use of interpolation techniques that can only offer an approximation.

This paper is divided into three main sections. The first examines the necessity to reorganise the spatial units used in the collection of data to meet the goals outlined by SDI policies at a corporate, local, state/provincial, national, regional (multi-national) and global level (Rajabifard, *et al.* 1999). The second outlines Hierarchical Spatial Reasoning (HSR) theory, which has been utilised in the development of numerous conceptual models to reorganise spatial boundaries within the state of Victoria, Australia. Finally, a third section outlines the issues found in the development of a GIS based algorithm aimed to automate the design of administrative boundaries according to HSR principles.

2 THE PROBLEM

It is well recognised that a rigorous SDI can enhance spatial data management (Rajabifard *et al.* 2000). Administrative and political boundaries constitute essential layers within the SDIs that must be co-ordinated if effective data integration and analysis between organisations and data layers is to eventuate. However, historically, countries have divided social, economic and political responsibilities amongst a variety of organisations. In turn, these organisations have established independent administrative, planning and political boundaries that rarely coincide, (Robinson and Zubrow, 1997; Huxhold, 1991). Due to the structure of boundaries as polygons, problems occur when technology such as GIS is used to integrate and cross analyse data based on these non-coterminous boundary units. Therefore, to empower SDI framework implementation and an optimum level of analysis in the spatial information industry, technical issues of increasing the usability of data require attention.

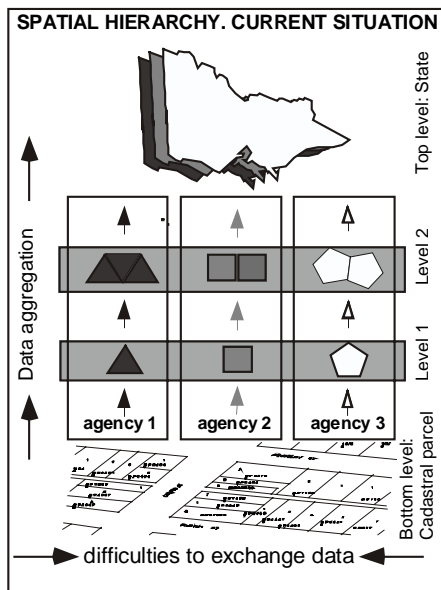


Figure 1. Current hierarchical spatial structures; the problem

Adopting the case of the State of Victoria (Australia), figure 1, illustrates the current situation where each agency establishes a different size and shape of spatial unit, based on their individual and often unique requirements using the land parcel (in most cases) as the bottom layer. In turn each organisation aggregates these boundaries in a hierarchical fashion to cover the state. Data aggregation is possible for each organisation however, under this current system, additional methods must be employed to facilitate the cross analysis between organisations (Eagleson *et al.* 1999).

The significance of this research into the co-ordinated structure of boundaries is highlighted in First Symposium of GIS in Health, Melbourne 1997, (Escobar *et al.* 1997) where the problem of incompatible boundary alignment restricts the implementation of GIS for health service planning. Medical institutions often attach data to postcodes derived by Australia Post, while demographic data is attached to collector district boundaries making accurate analysis between these non-coterminous boundaries virtually impossible. The analysis of child immunisation statistics demonstrate this fittingly. The records detailing the number of children immunised are attached to postcodes, to calculate if this number is below or above the average population data is required. However, due to the incompatible alignment of postcode and collector district boundaries, demographic data cannot be cross analysed with medical information. Thus, without additional information it is impossible to establish if child immunisation rates, within a particular postcode district, are below or above an acceptable limit, restricting the accurate planning of health services.

As the powers of GIS for data analysis increase, countries worldwide are realising the problems associated with incompatible boundary alignment often termed the “spatial hierarchy problem”. Currently solutions are being sought which involve either the interpolation of data from one boundary set to another, or the re-aggregation of point data into a number of different boundary systems. Unfortunately, due to the problems associated with confidentiality, accuracy and cost, neither data interpolation nor re-aggregation provides an optimal solution to the problems associated with uncoordinated boundary alignment. A proposed solution entailing the re-organisation of boundaries into one structured system based on the properties of HSR is detailed below.

3 HIERARCHICAL SPATIAL REASONING (HSR)

Currently, hierarchical principles are used in an array of different disciplines to break complex problems into sub problems that can be solved in an effective manner (Timpf and Frank, 1997). Although spatial hierarchies are designed using the same principles – to break complex tasks into sub tasks or areas – relationships between levels within the hierarchies are complex. This complexity is primarily due to space being continuous and viewed from an infinite number of perspectives at a range of scales (Timpf and Frank, 1997). In the past much research has focussed on the properties of two-dimensional hierarchical structures to model networks, such as road and drainage systems. One prime example is the use of HSR in modeling wayfinding through cities (Car, 1997).

The benefits of furthering HSR theory to the organisation of administrative polygon layers vested in its properties. The first of these properties is *Part-whole*. This property relates directly to the relationship between elements as each element within the hierarchy forms a part of the elements on the layers above and a whole of the elements below (Palmer, 1977). This principle is directly related to administrative boundaries as each boundary is formed through the successive aggregation of smaller boundary units to form larger administration units.

The second is the *Janus effect*. This property was first introduced by Koestler (1968) and is named after the god with two faces, where each level in the hierarchy has two faces. One facing the levels below and one facing the levels above. In effect, each primary administration polygon has two faces, one generally looking to the smaller cadastral parcels from which it is formed and a second looking towards the larger administration units which it forms.

The third property is *Near Decomposability*. This property is related to the nesting of systems, and based on the fact that interactions between various kinds of systems decrease in strength with distance (Simon, 1973). Near Decomposability also applies to administrative polygons, as boundary systems are often nested within one another from the parcel base through to a country border. Additionally the relationship between elements (administrative polygons) decreases with distance.

3.1 HSR theory applied to administrative polygons

It is envisaged that the utilisation of HSR theory to co-ordinate various agency boundaries within a common hierarchical spatial framework has the ability to revolutionise data integration and analysis methods. Figure 2 adopts the Australian example to illustrate the proposed model where a cadastre, common to all states, provides the foundation, with the national boundary at the top level of the spatial hierarchy. The spatial boundaries of different agencies are organised in a co-ordinated hierarchical system implemented by the application of HSR theory, (Car, 1997). Data exchange and aggregation is possible inside, and among individual agencies providing aggregated data at all levels and amongst all agencies.

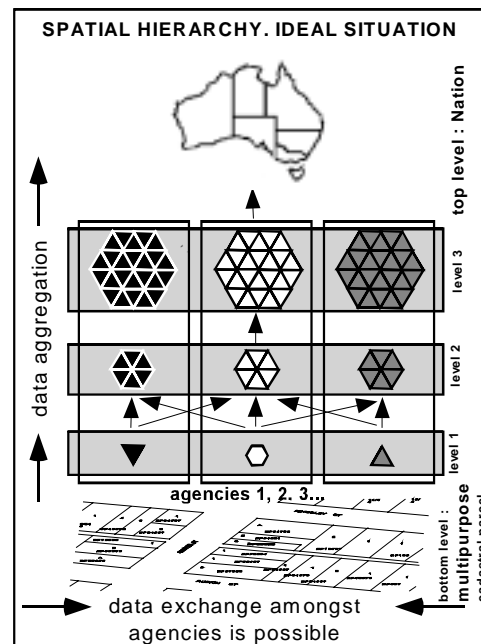


Figure 2. Future hierarchical spatial structures; the solution

4 ADMINISTRATION POLYGON DESIGN

Reis and Raper (1994) report the construction of boundary delineation systems using GIS techniques, is a poorly studied field. One contributing factor to this field not being researched in greater depth, is the fact that most boundary systems have evolved before GIS was developed. Therefore, many boundary systems have been drafted on hard copy maps. However, with advances in technology, these maps have been digitised for GIS incorporation. Prime examples of this evolution of boundaries from analogue to digital format are postcode and census collection district boundaries of Australia. In contrast,

few examples exist where new boundary systems have been created using technology such as GIS for the intelligible design of spatial boundaries. Consequently, administrative boundary systems have been transferred into the computer environment without utilising the spatial analysis functions inherent in a GIS.

As discussed previously, countries around the world are confronted with similar problems in establishing boundaries. One way to minimise the problems discussed above and improve the functionality of the boundaries, is to distinguish a number of criteria to support the boundary definition process. Hugo *et al.* (1997) have compiled TABLE 1 from a number of countries world-wide and the criteria set in the establishment of small unit boundaries. The constraints placed on administration boundaries varies in each country depending on their level of geocoding of individual parcel information and the level of confidentiality restrictions (Hugo *et al.* 1997). In comparison, the system designed in this paper aims to adhere to a number of these criteria in addition to criteria required by the ABS and Australia Post (AP).

TABLE 1

LIST OF CRITERIA USED OR RECOMMENDED BY SIX COUNTRIES FOR THE DELINEATION OF BASIC SPATIAL UNITS (BSU) FOR THE DISSEMINATION OF STATISTICS

	Criteria	Countries
1	BSU must not cross any higher-order boundary	CFNSUZ
2	BSU boundaries must be clearly shown on maps	CFSUZ
3	Newly defined BSU boundaries must be as consistent as possible with those used in previous census	CNSUZ
4	BSU boundaries should separate out urban settlements from rural	CSUZ
5	BSU boundaries should conform to some population range	CNUZ
6	BSU boundaries must be clearly visible on the ground	CUZ
7	BSU areas should not be to large	NUZ
8	Road or communication line should form central artery of BSU, binding it together by giving accessibility	CNS
9	Larger uninhabited areas may/should form zero population BSUs	ZN
10	BSU should be homogeneous as possible in their physical and economic attributes	N
11	BSU should form connected agricultural areas suitable for agricultural planning	N
12	Each BSU must constitute a convenient collector workload	C
13	BSU are to consist of all polygons whose edges are formed by the intersection of visible linear features	U
14	Physical barriers like forests, ridges etc. should be used as BSU boundaries	S
15	BSU boundaries should be chosen to be acceptable to as many government departments as possible	S

Where, C = Canada, F = Finland, N = Norway, Z = New Zealand, U = USA, S = Sweden

(Hugo *et al.* 1997 adapted to include the proposed Victorian system)

4.1 Administration boundary constraints

The following section aims to introduce the constraints utilised in the delineation of administrative boundaries as required by ABS and AP. These criteria specifically involve the protection of confidentiality and the establishment of identifiable boundaries that are of practical shape. In consultation with ABS and AP the following criteria were established.

- It was determined that to be easily identifiable and facilitate routing, the boundaries where possible should follow roads and not cross any major topological barriers
- Boundary shape is also important as the units are often used in the display of demographic statistics and in allocating management responsibilities.

In summary confidentiality, topographic features and boundary shape have all been identified as the major criteria in the establishment of administrative boundaries for the ABS and AP in the state of Victoria, Australia.

5 PROTOTYPE DEVELOPMENT

The implementation of a spatial hierarchy requires a technical solution. This technical solution has been divided into two components, data and conceptual models through which aggregation can occur. This prototype has been developed primarily upon four main data sources. These sources include the AP address point data base, the cadastre, the road network and the topographic data base. Each of these data sets are briefly detailed below.

(a) Cadastre

When combining GIS and hierarchical reasoning, it is obvious that the most detailed boundary system is predetermined by most detailed data stored in the system. Administrative units can be created from this initial coverage by classifying the categories into more general categories (Volta and Egenhofer, 1993). For this reason, coupled with the importance of the cadastre in relating administration policy and procedures to the owners and residents of the land, it is intended that the primary infrastructure for a hierarchical boundary structure in Victoria is the cadastre. The cadastre has been defined as:

“a parcel based, and up-to-date land information system containing a record of interests in land (e.g. rights, restrictions and responsibilities). It usually includes a geometric description of land parcels linked to other records describing the nature of the interests, the ownership or control of those interests, and often the value of the parcel and its improvements. It may be established for fiscal purposes (e.g. valuation and equitable taxation), legal purposes (conveyancing), to assist in the management of land and land use (e.g. for planning and other administrative purposes), and enables sustainable development and environmental protection.”

(International Federation of Surveyors, 1995)

(b) Building data / Address data

Due to many dwellings residing on the one block of land, which is often the case in urban areas, the Address database was utilised. This database allows the model to incorporate the number of buildings into the model and is used as an indication of the number of persons living within a parcel of land.

(c) Mesh Block

The second layer of the prototype was created manually through the development of the mesh block. The development of the mesh block involves the segmentation of the data in metropolitan areas along road centrelines (Figure 4). This model is based on the current system utilised as the basic building block for administration units in New Zealand, (Webster, 1999). In this system, blocks are formed using the road network to form polygons surrounding cadastral land parcels. These polygons are relatively small and form an intermediate unit for aggregation between the land parcel and the next layer of the hierarchy – the small collection unit. By utilising this method, a number of key criteria in the building process are realised. Firstly, the system aligns boundaries with cadastral land parcels. Secondly, mesh blocks are devised systematically on the road network, and as a result are free of any operator bias. Thirdly, the system is rigorous and every land parcel will be selected through the process.

It should be noted that the mesh block units are not intended for the display of data that is subject to confidentiality restrictions. However, they do provide a rigorous base for selection and aggregation into higher levels of the administrative polygon layers. To ensure that topographic boundaries remain complete, this mesh block layer was intersected with major topographic boundaries.

(c) Topographic features (natural barriers)

Topographic features such as major waterways and major road structures have also been utilised within the system. These topographic features provide the barriers of natural divides which administrative boundaries should not cross.

5.1 Methods of Selection and aggregation in the GIS environment

The following section examines the strengths and weaknesses of four conceptual models trailed by the authors in this project, each designed specifically for selecting and aggregating polygons into administrative boundaries within the GIS environment.

These include:

- Model 1 - Interactive boundary delineation,
- Model 2 – Thematic selection,
- Model 3 – Spatial selection using Thiessen polygons and,
- Model 4 – Thiessen selection based on existing boundaries.

Each model has been tested on a test site located in Melbourne, Australia. In developing the models the following criteria which has been described by Car (1997) as imperative to the success of HSR models have been consulted.

- A hierarchical structure and a method to transform a 'flat' non-hierarchical data space in an equivalent hierarchical one,
- A rule how to reason on such a structure,
- A comparison of the results of the hierarchical algorithm with the results of the non-hierarchical one, and
- Performance analysis

(Car, 1997, Timpf and Frank 1997)

As a result of testing the models against these and other criteria, a selected model has been developed into a prototype for the automatic allocation of administrative polygons.

Model 1 – Interactive Selection Method

The interactive selection of administration polygons involves the overlay of numerous key layers of spatial data. Once overlaid, operators are able to manually delineate

boundaries. The advantage of this model is that numerous key data sets can be consulted. However, many disadvantages are involved in the interactive selection process. One major disadvantage of interactive boundary design is the time taken as it may require several weeks to cover a region and even then the boundaries may be inadequate as they are subject to human error and bias. Additionally, the method does not readily conform to the methodology of HSR. This is due to the subjective nature and non-repeatability of methods used in interactively establishing boundaries. Although many disadvantages exist in this methodology, it is important to recognise that these methods do exist and in some circumstances may provide a viable means for the creation of administration boundaries such as the one presented by Lopez-Blanco (1994) in determining environmental units for land management. Therefore, automatic means for computation have been investigated through methods of spatial and thematic selection processes outlined below.

Model 2 – Thematic Selection

In order to improve performance and reduce the level of human bias from model one, model two was derived. This model is based on the initial selection of starting polygons followed by the process of aggregating surrounding polygons into a spatial hierarchy. Simplistically, the algorithm is founded on the acceptance or rejection of polygons according to constraints. If the polygon does meet the constraints then accept it, if the constraints are not met then reject the polygon from the selected set.

There are numerous ways that thematic methods can be applied. Initially a spatial selection process is required for polygon selection. Following the initial selection routine, surrounding polygons can be selected by adjacency, distance or shape. Each of these selected polygons are subject to constraints to ensure the functionality of the boundaries and that HSR requirements are met. Constraints built into this system guarantee requirements as confidentiality, shape and contiguity of polygons. This thematic selection method does meet the criteria outlined for effective HSR (as previously outlined) as the system utilises rules as a method for transforming the 'flat' non-hierarchical data space into an equivalent hierarchical structure. In turn the constraints derived at each level provide a method for reasoning on the structure. Comparisons and performance analysis between the non-hierarchical and the hierarchical structure are both possible.

Model 3 - Spatial Selection - Thiessen Polygons

Martin (1998) has explored the use of Thiessen polygons for the development of census output areas. Model 4 is also based on these principles.



To utilise the test data described above and the GIS software Arcview (ESRI), a grid of points is derived which is based on the density of land parcels, (this attempts to meet the confidentiality related issues). Once the grid has been established, Thiessen polygons are generated utilising the ArcView extension obtainable from the ESRI web site (www.esri.com). The result is a number of polygons overlaying the mesh blocks. Figure 3 illustrates this overlay. Consequently, each mesh block is allocated an identifier based on the Thiessen polygon overlay and whether or not the majority of the mesh block is contained within the polygon. Common boundaries between polygons are then

dissolved establishing the next layer in the spatial hierarchy. This method can then be repeated using additional constraints to meet the needs of users of the next layer of the hierarchy.

The process of Thiessen polygon selection has the advantage of being a fast and rigorous method of mesh block selection and aggregation. However, disadvantages exist in the location of meaningful points from which the Thiessen polygons are established. If possible it would be desirable to use monuments that bring with them a sense of community or culture to the process of defining boundaries.

Model 4 - Thiessen Selection based on existing infrastructure

Model four capitalises on the Thiessen concept derived in model three above. However this model assumes a network of boundaries already exists. This model simply facilitates the alignment between the cadastre, road network or other underlying infrastructure and the administrative boundary layer. The method of establishing centroids based on existing administrative polygons enables the creation of Thiessen polygons. Land parcels are then selected based on these Thiessen polygons. For instance if the boundaries exist, the Thiessen polygons can be rapidly calculated and the existing administrative boundary system aligned with underlying infrastructure. This method is based on the methods of Boyle and Dunn (1991) whom have been previously utilised a similar method for estimating areal boundaries around centroids. The method is simple yet rigorous as contiguous boundaries are established. Although this method is simple, it has the disadvantage of being dependent upon the existing boundary infrastructure. As a result, problems related to the initial boundary design process may lead to errors in the final result.

5.2 Model Summary

The variety of models presented in this paper demonstrates the advantages and disadvantages inherent to each method depending on different circumstances. Table 2 compares the strengths and weaknesses of the models against numerous implementation factors. These factors include: relative processing time, design flexibility, and how the model compares against the criteria established for the successful implementation of HSR theory.

TABLE 2
COMPARISON OF CONCEPTUAL MODELS AGAINST IMPLEMENTATION CRITERIA

	Model 1 Interactive Selection	Model 2 Thematic Selection	Model Thiessen Selection	Model 4 Existing Boundary Selection
Time	Very Slow	Medium	Fast	Fast
Flexibility	High	High	Low	Low
Compliance with SHR	High	Low	Medium	Dependent on existing infrastructure
Level of Operator Bias	High	Medium	Low	Low
Temporal Stability with Existing Systems	High – if current boundaries are used to support the design	Low	Low	High
Repeatable	Low	High	High	High
Rigorous	Dependent upon operator	Low	High	High

By working with the infrastructure of data sets available in Victoria and the constraints required by both AP and the ABS it was decided to program a generic algorithm based on a combination of spatial and thematic selection techniques (model 2). The following section details the data sets on which the prototype is to utilise.

5.3 Prototype Overview

The automatic boundary creation algorithm was undertaken using Avenue, an object-oriented programming language that operates under ArcView, the desktop GIS software developed and distributed by ESRI.

In assessing the capabilities of GIS in the delineation of administrative boundaries, the authors tested a number of aggregation methods. The first involved aggregation through the selection of adjacent polygons, the second was selection through the shortest distance to polygon centroid and the third was selection by shape. Due to the impact that shape can have on the functionality of the boundaries it was decided that selection by shape is the most viable alternative. This methodology selects an initial polygon. The method then assesses which of the adjacent polygons, when joined with the initial polygon, will yield the most compact result based on the reason of circularity index. This index has been adapted from Tomlin (1992), and is broken into the following components detailed in equation 1.

$$RC = \sqrt{\frac{SZ}{SC}} \quad (1)$$

RC = Reason of circularity
 SZ = Surface of the current zone
 SC = Surface of circle having the same perimeter.

(Source: Tomlin, 1992)

As the reason of circularity approaches 1, the polygon in question approaches a circular shape. As the reason of circularity approaches 0 the polygon in question becomes irregular. Therefore, once an initial polygon was selected, the adjacent polygons were tested against the reason of circularity. The polygon with the highest reason of circularity (highest value approaching one) is selected and the common boundary between the two mesh blocks is dissolved. This process is repeated until the frequency required for confidentiality is reached.

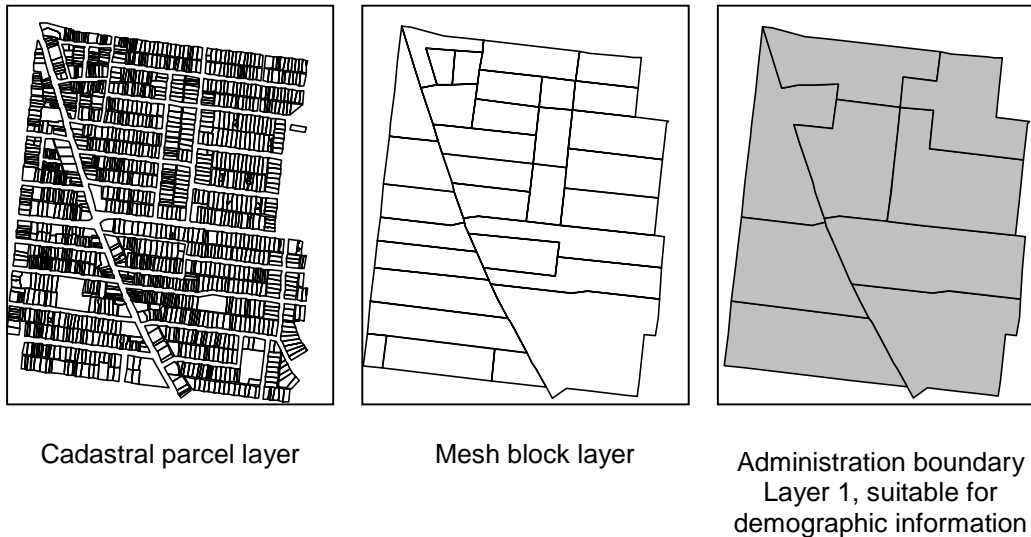


Figure 4, Illustration of the progression of aggregation from cadastral parcels, to mesh block units through to administration units created automatically using the prototype developed by the authors.

6 CURRENT RESEARCH

Current research includes programme testing and implementing the GIS prototype for automatic boundary allocation, based on the theory of HSR. In particular, issues need to be overcome in detailing the criteria of rural boundaries where the criteria for establishing administrative boundaries is often vastly different from metropolitan areas. For example in rural regions, roads often unite communities rather than segment them as is assumed in city areas. Therefore adaptations to the model are required to suit rural regions.

7 CONCLUSION

This paper details the current problems associated with non-coterminous boundary systems and details ongoing research into the development of a method for the automated delineation of administrative boundaries. In response to this problem a number of conceptual models have been developed. Each of these models aims to utilise the theory of HSR, SDIs and GIS technology to delineate functional administrative boundaries. Once the models were evaluated against a number of criteria, model two, based on a combination of thematic and spatial selection techniques, was identified as the most appropriate method in metropolitan regions.

The implemented algorithm offers a solution to the problem of boundary delineation and provides the means for accurate data exchange between agencies. It facilitates a quick, objective and improved method to administrative boundary subdivision.

Current research is being undertaken into refining the prototype to incorporate a greater number of constraints to meet the requirements of a large number of agencies within both rural and urban areas.

Future research will include the incorporation within the algorithm of factors related to social issues in boundary delineation, such as identity of place and spatial cognition.

It is through initiatives such as the one detailed in this paper coupled with effective data management strategies that the full potential of spatial data and SDIs can be truly realised.

8 ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the support of Land Victoria (LV) of the Victorian Government, Australian Research Council (ARC) (Grant No. S499714) and the members of the Cadastral Systems and Spatial Data Infrastructures Research Group at the Department of Geomatics, the University of Melbourne, (http://www.geom.unimelb.edu.au/research/SDI_research/) in the preparation of this paper and the associated research. However, the views expressed in the paper are those of the authors and do not necessarily reflect the views of LV, ARC and the Department of Geomatics.

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