Sustainability in the Information Society

15th International Symposium Informatics for Environmental Protection, Zurich 2001

Lorenz M. Hilty, Paul W. Gilgen (Eds.)

Part 2: Methods/Workshop Papers

UMWELT INFORMATIK AKTUELL

metropolis

Thinh, N. X. et al. (2001) in: L. M. Hilty, P. W. Gilgen (Eds.): Sustainability in the Information Society
15th Symposium Informatics for Environmental Protection, metropolis Verlag Marburg, 559-567.

Pin-pointing sustainable urban land-use structures with the aid of GIS and cluster analysis

Nguyen Xuan Thinh, Günter Arlt, Bernd Heber, Jörg Hennersdorf, and Iris Lehmann[1]

Abstract

As part of the national and international campaign to achieve the goal of sustainable development the search for sustainable urban form is in full swing. But the relationship between urban form and sustainability is currently still hotly debated. The need for more scientific and objective knowledge leads to a whole range of research to measurement of the physical compactness of urban settlement patterns. However the term "compactness of a city" has been defined by many only qualitatively. This induces us to create a ARC/INFO-database of land use patterns and to model the physical compactness of 116 regional cities in Germany (administratively autonomous municipalities). Moreover we calculated the degree of sealing and land price of these cities. There are many examples of claims and counter-claims within compact city theory. For example, it is claimed that the compact city protects the countryside; the counter-argument is that ecologically important urban green spaces are lost. Also it is claimed that the compact city can improve the economic attractiveness of an area; but it could be argued that the compact city generates higher land prices, making housing and business premises prohibitively expensive. For these reasons we carried out the Cluster Analysis for the 116 cities with the variables degree of sealing as an ecological indicator and land price or gross value added per m² of settlement areas as an economic indicator in order to find out the sustainable balance between ecological and economic performance potential.

1. The sustainability and compactness of cities

From the time towns began to emerge some 10,000 years ago, they were designed with defence in mind. So as to minimise the length of protective perimeter walling required and keep the number of access points down, functions bothersome to the community or taking up too much space were sited 'beyond the pale' (examples being graveyards, shooting ranges, mills, livestock markets). This resulted in compact forms of settlement. With the advent of industrialisation, urban structures changed

[1] Institute for Ecological and Regional Development, Weberplatz 1, D-01217 Dresden, Email of the corresponding author: Nguyen.Thinh@ioer.de, Internet: http://www.ioer.de

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dramatically. Modern warfare led to defensive walls being demolished. At the same time, the expansion of industry and transport systems ushered in an unprecedented process of urbanisation that persisted until well into the 20th century. Urban development was now synonymous with urban expansion. Towns grew into their surroundings unabated. This proliferation outwards was accompanied by an atrophying of the centre, producing enormous discrepancies. Urban planners today, therefore, urgently need to pin-point survival strategies for the city of the future. And - as current debate on urban design has shown - such strategies are drawing on the historically evolved compactness and density of towns, precisely the factors that enabled them to thrive as living and built environments in the first place. Alongside the model of the "network city" - the sprawling metropolis -, urban development is also addressing itself to the model of the "compact city", whose benefits are seen as being its improved accessibility on foot and improved neighbourhood relations. Such deliberations are especially apt in the context of sustainable urban development.

For the British architect Richard Rogers, designer of the Centre Pompidou in Paris and the Millennium Dome in London, the key to urban sustainability lies in reinterpreting - re-inventing - the dense and varied, compact urban fabric in which activities overlap (Rogers 1995). In The European Commission's Green Paper on the Urban Environment of 1990 (Breheny 1992), it is argued that the principal advantage of the compact city rests in its contribution to sustainable urban development. Virtually all urban development concepts produced in recent years embody the aim of creating compact cities (Beatley 2000). Hence it is not surprising that the ideal of the compact city is set to become a point of reference, a guiding star, for urban planning and policy in the 21st century (Deimer 1998).

The route towards a compact city is long and arduous, however, as the controversial nature of debate on the issue has demonstrated (Breheny 1992 and Jenks et al. 1996). Questions as to which type (physical or functional, for example) and degree of compactness are conducive to sustainable urban development have yet to be answered for the most part. Initial findings from the measurement and evaluation of the compactness of German cities are provided by a research project completed in 2000 by the Institute for Ecology and Regional Development in Dresden (Arlt et al. 2000).

2. Goal, Methods and Database

The research project aims to point up causal connections between land-use structures and the economic and ecological performance potential of cities. Urban land-use structures (Urban form) are defined as a framework of spatial relations between lands with differing uses and hence are also expressions of a spatial configuration of functions examined in the course of the research project on the basis of structural models, GIS analysis and multivariate statistical procedures. This resulted for one

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thing in a “degree of compactness” indicator with which the spatial configuration of urban functions can be measured and evaluated. The database embraces indicators and information for 116 administratively autonomous municipalities, the entirety of such entities in Germany with the exception of Eisenach.

A geodatabase of land-use structures in the 116 municipalities plus their urban environs was produced by means of independent digitalisation incorporating CORINE data and DLM data (Digital Landscape Model of Germany) together with topographical maps. This database can also be used for further extensive research purposes. It was used to establish and validate the degree of surface sealing [%] for the 116 municipalities with the aid of a structure-type approach. It was possible to show that the degree of surface sealing is an indicator of a city’s ecological performance potential. The degree of surface sealing was used as an indicator for a city’s ecological performance potential.

Overall land prices [DM/sq. m.] in the 116 cities were computed in the form of cyclically adjusted purchase values for developed land between 1991 and 1996 relative to the base year, 1995. Using regression analyses, it was possible to demonstrate a significant correlation between developments in the overall municipal land price and gross value-added per unit of settlement and transport landtake. In this way, it was possible to confirm correlations as posited in ground-rent theory between earnings accruing from the use of land (in the form of gross value-added) and the price of land as a secondary phenomenon of ground rent. Hence, the average cost of land can serve as an indicator of economic performance potential at the level of scale of the overall municipal entity.

3. Assessing urban compactness with the aid of GIS raster analysis and the gravitation approach

Urban researchers have recently been increasing efforts to measure and study urban compactness. Hitherto, however, definitions of the term “compactness” have for the most part been blurred or merely qualitative (Apel 1997, 58; Ponel 1999, 128). The known quantitative measures of compactness have the considerable drawback of not recording spatial distances between individual settlement areas and hence of not being able to mirror the varying degrees of dispersion in urban structures. It is accordingly necessary to develop a different means of measuring urban compactness.

We now wish to present a new methodology for measuring compactness based on the Urban form GIS raster analysis and resorting to the gravitation approach. A square raster network on a 500 x 500m grid is placed on top of the Urban form. The surface-sealed area in each grid cell is quantified. Subsequently, abstraction to raster cells containing more than 5 sq. m. of sealed surface is effected. N is taken to be the total number of all raster cells with a sealed area greater than 5 sq. m. To an extent, the figure N indicates a city’s territorial size. For each pair of raster cells i and j (i =

1 (1) N-1, j = i+1 (1) N) with sealed areas Zi and Zj, the reciprocal power of attraction is computed by analogy with the law of gravitation

$$A(i,j) = 1/c * Zi * Zj / d^2(i,j)$$

with d(i,j) representing the Euclidean distance between centres of cells i and j and c = 100 m² being a proportionality factor (A(i,j) is rendered non-dimensional through c). The degree of compactness is established as a mean value in the gravitation matrix:

$$T = \Sigma A(i,j) / [N (N - 1) / 2].$$

T is a medial measure of spatial interaction between area clusters (aggregates) and also reflects the degree of spatial dispersion of the urban settlement structures investigated. The more extensively a city's built-up areas are scattered, i.e. the more punctured (lacunate) its urban structures are, the weaker the spatial interaction between the city's clusters is. Conversely, spatial interaction between a city's clusters is stronger when the city's structures are more compact and hence when T is greater.

The calculation model delineated was integrated into GIS ARC/INFO by means of Arc Macro Language programming. This allows the degree of compactness to be automatically computed and input by GIS personnel to be greatly reduced. Given a 116-city study, that is particularly beneficial. Task-related simulations can be conveniently conducted, moreover, e.g. studies of the impact of grid size on the assessment of compactness by calculating T for a further 9 grid sizes 100 x 100 m, 200 x 200 m, 300 x 300 m, 400 x 400 m, 600 x 600 m, ... , 1000 x 1000 m. The degrees of compactness identified for the 116 cities in respect of two different grid sizes reveal a high level of correlation. A mean value derived from the 10 degrees of compactness was formed for each city in accordance with the grid sizes selected. We were able to ascertain in this way that there is a strong correlation between these mean values and the degrees of compactness of the 116 cities obtained for the grid size 500 x 500 m (r = 0.99). This proves the case for selecting grid size 500 x 500 m.

The histogram on the compactness of cities (Fig. 1) reveals a largely lop-sided distribution amongst administratively autonomous municipalities to the left and indicates a dispersed to strongly dispersed distribution of settlement and transport landtake for fifty per cent of towns and cities (degree of compactness less than 10). The lower the degree of compactness, the more countryside a city consumes. Of 116 municipalities, 31 (27 %) are partially compact, 16 (14 %) compact and 11 (9 %) very compact. This evaluation of urban-planning development was supplemented by and interlinked with analyses of socio-economic data for the towns and cities under consideration. Only the cluster analyses are to be addressed in detail in this article. Subsequent analysis of the structural characteristics of clusters can help extrapolate benchmark values and recommendations for sustainable urban development.

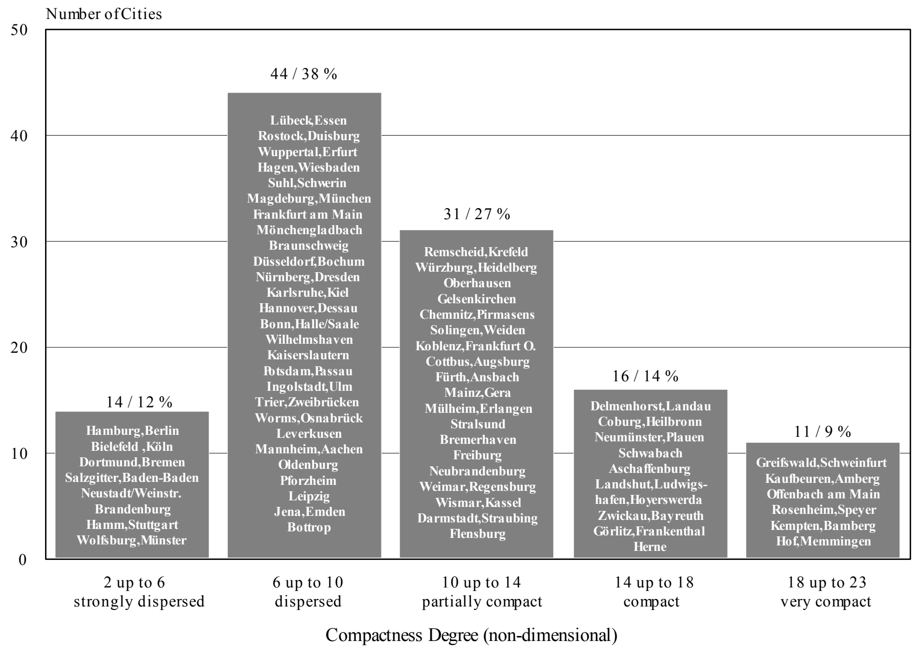

Figure 1

German cities – frequency distribution according to the compactness degree

4. Cluster analyses with a view to balancing the economic and ecological performance potential of towns and cities

The cluster analyses conducted as part of the project aim to provide answers to the question as to the impact of land-use structures on the performance potential of towns and cities. The municipalities within a given cluster are intended to be largely level pegging in terms of economic and ecological performance. It is posited that there are typical and performance-specific use structures that can be reflected in clusters of cities with very differing but also balanced economic and ecological performance levels. Given the existence of differing economic and ecological situations, it seemed reasonable to develop cluster variants for all administratively autonomous municipalities in Germany as well as such that are divided along East/West German lines. Drawing on the database established, the following 11 attribute variables were selected that significantly characterise a city's land-use structures and go a long way towards moulding its economic and ecological performance:

(1) settlement and transport landtake as a percentage of the urban area

(2) population density in inhabitants per square kilometre of city area
(3) settlement density in inhabitants per ha. of settlement areas and transport land
(4) recreaction area provision measured in square metres per inhabitant
(5) open space provision measured in square metres per inhabitant
(6) degree of sealing in urban nucleus as a percentage
(7) eco-value of urban nucleus (non-dimensional)
(8) gross value-added measured in DM per square metre of urban space
(9) gross value-added in DM per m² of settlement areas and transport land
(10) land price in the form of purchase values for developed land (DM/sqm.), and
(11) unemployment rate as percentage.

The first cluster analysis with these variables and a subsequent discriminant analysis revealed that two variables suffice to distinguish cities, notably either variables (6) and (9) or (6) and (10). Given the three scenarios involved (all, West and East Germany), and the two sets of variables, six cluster variants were developed by the SPSS program using the Ward procedure.

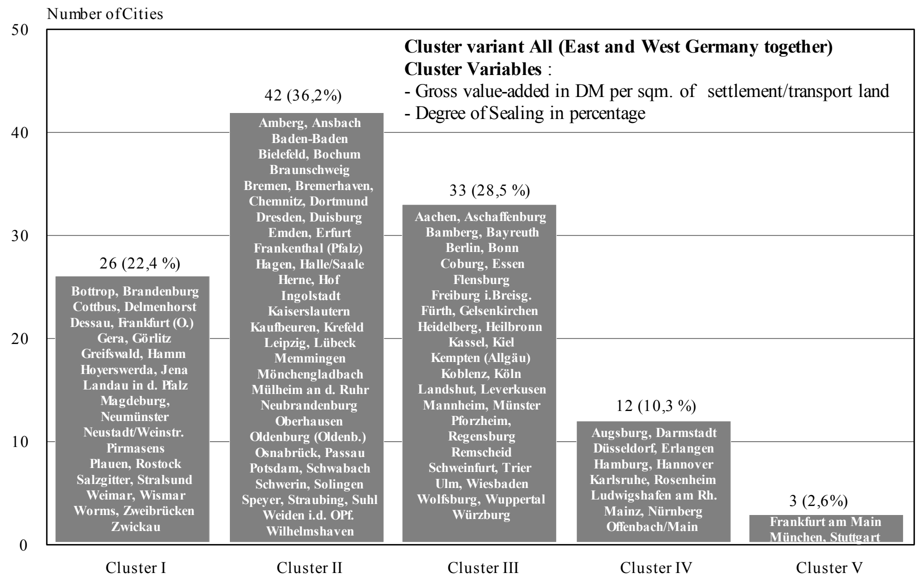

Figure 2
German cities – frequency distribution according to the result of the cluster variant all Germany (East and West Germany together)

Figure 3
The mean and extreme values of 9 indicators for each cluster of the cluster variant all Germany (East and West Germany together)

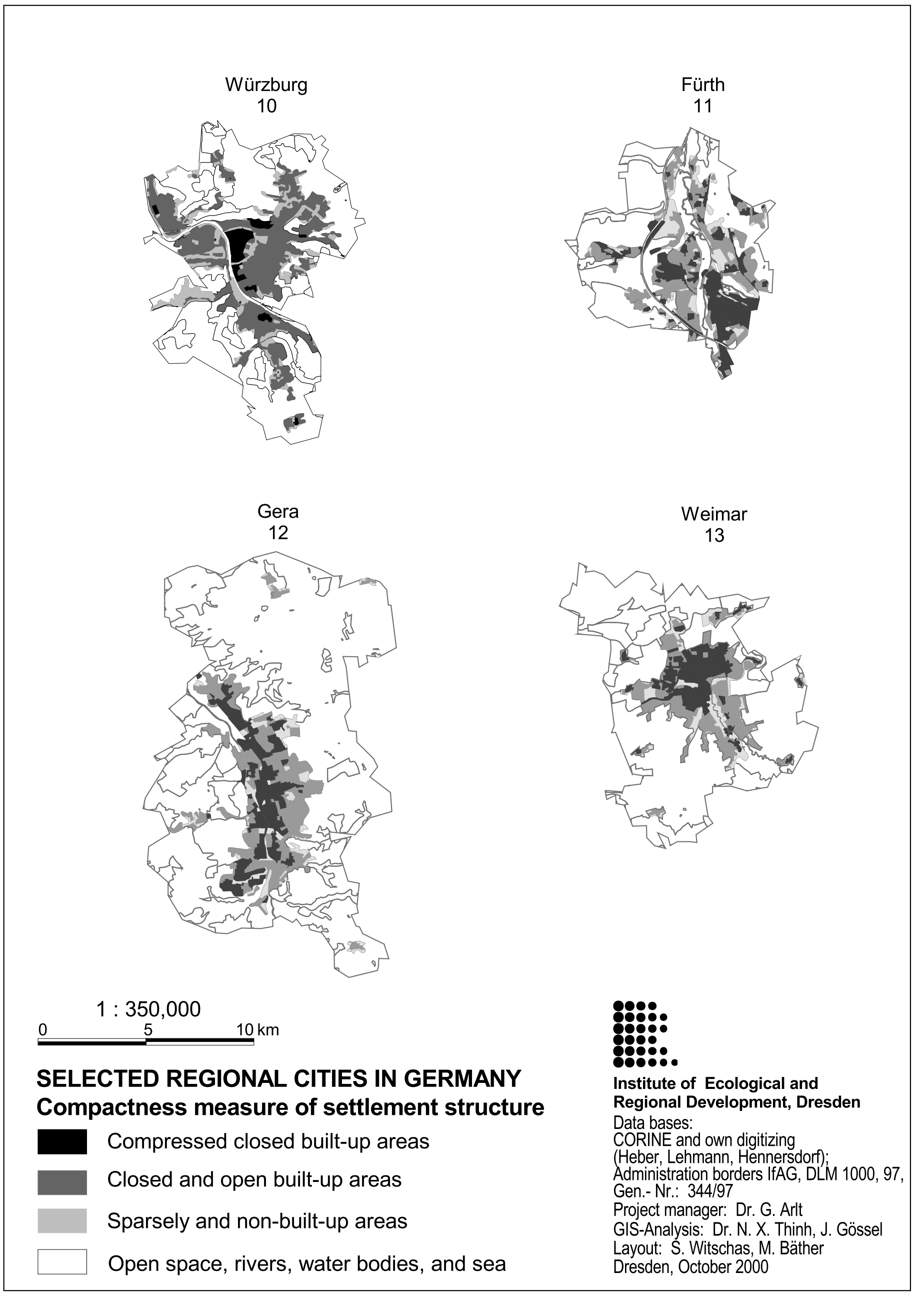

Figure 4
The compactness of four cities as representatives of all Germany, West Germany, and East Germany (Gera and Weimar) for economic and ecological balance

As a means of arriving at conclusions and benchmark values, clusters were investigated in respect of 11 indicators characterising the economic, ecological and use-structure situations of the municipalities in question. Drawing on the 11 indicators, cities were identified that constituted the median and extreme values for each cluster (see Fig. 3, in this figure only 9 indicators were illustrated). The mean values for the different clusters produce urban-type patterns that reflect the latest knowledge from impact analysis on the interrelations between use structures and economic as well as ecological performance potential. The mean values for the different clusters can be looked upon as urban-type starting and framing conditions under which development strategy can be geared to reflect varying urban types. Such an alignment initially involves what can be referred to as "pointer" mean values derived from mean values for the indicators applied to urban clusters. These mean values can be regarded as "pointers" because they render visible and measurable structural differences obtaining between municipalities with comparatively balanced economic/ecological performance potential and those that are commercially strong or weak. This strategic alignment embraces the development of settlement areas and transport land, the re-utilisation of derelict and conversion lands, the development of urban-planning density, open land and open spaces, and the development of land-area productivity.

In city cluster III of the 6 variants, for which balanced economic and ecological performance potential is assumed, all Germany and West Germany are both represented by Würzburg and Fürth (Fig. 2 and 3) while Gera and Weimar figure for East Germany. All four of these municipalities are relatively compact (Fig. 1 and 4). Weimar is plausible as a representative for economic and ecological balance and corroborates material considerations and mathematical analysis.

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