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Measuring compactness of locality in Israel

Note by the Central Bureau of Statistics of Israel

Summary

The study deals with measuring patterns of urban locality development on a continuum from compact to sprawled. Compactness is commonly associated with a concentrated development within a boundary of a regular shape, as opposed to dispersed and fragmented development, which affects the costs of infrastructure and public services. This study is commissioned by the Ministry of the Interior of Israel, in the framework of a more extensive project that aims to characterize the Israel local authorities by a variety of indicators, relevant to providing the municipal services to the local authority population.

The Index of Compactness is constructed for 197 municipalities and local councils in Israel, based on their development characteristics in 2006. The level of compactness for a given locality is calculated as a combination of several dimensions of an urban locality pattern, including configuration, concentration, space filling, internal continuity and intensity of land use. Each one of these dimensions is also a construct, which can be measured in a number of ways.

Keywords: measure of compactness, measuring sprawl, spatial dimensions, pattern of urban development, land use.

I. Background

1. The term 'compact' and its opposite 'sprawl' are widely adopted to characterize patterns of urban and rural development. Sprawl is characterized by low density, remoteness from central facilities, spatial segregation of land uses, leapfrogging and strip development (Galster et al., 2001; SCATTER Project, 2002-2004). Although compactness and concentration have their problems (metropolitan congestion), there is a general consensus in the literature that dispersed and fragmented patterns are harder to service and costlier to interact with, so that the overall ecological, economical and social effects of non-compact development are negative. Sprawl generates higher costs of infrastructure and public services, leads to wasteful use of energy, increases traffic congestion and trip times due to lack of public transit and high level of private car use, creates spatial and professional mismatch between population and employment.

2. In recent years much effort is put throughout the world to implement a concept of sustainable urban growth and compact city model. A vast amount of literature is devoted to measurement of compactness/sprawl. Although numerous measures are proposed and implemented, only few authors give the definition of the terms, and none of the definitions is more than a list of different aspects of development measured on a continuum from compact to sprawled. The lack of an accurate definition is explained by Ewing et al. (2002): *"Sprawl, and its antithesis compact development, are constructs, i.e. theoretical abstractions, such as 'intelligence' in education or 'utility' in economics. As such, they must be represented by operational variables (dimensions) that can be objectively measured. These variables may not completely represent the underlying constructs to which they relate, but they capture the essence of the constructs. The various dimensions of development that distinguish compact development from sprawl (density, land use mix etc.) are also constructs, which can be measured in many ways".* Even authors following more or less the same definition concept propose very different ways to measure the development pattern. The choice of a measure depends on the purposes of a specific project as well as on availability of data for its calculation.

3. Although there is no exact definition of the term, compactness is intuitively understood as non-dispersion or concentration. For an object consisting of separate and mutually remote elements this understanding may be expressed and measured in terms of closeness of the elements to each other or to some central point. Thus in Israel, compactness of a regional council, consisting of a number of localities, is measured by the average distance from the localities, included in the council, to its operational (municipal) center. Measuring compactness of a municipality or a local council is a more complicated matter, since these local authorities consist of a single locality and thus can not be considered simply as a number of separate elements. This study presents the computation of the index of compactness of Israeli municipalities and local councils, constructed as a combination of several spatial dimensions of urban development.

II. Basic aspects

4. A compact locality is commonly associated with a concentrated development within a boundary of a regular shape, as opposed to dispersed and fragmented development. Among numerous dimensions of urban development mentioned in the literature, three main aspects can be distinguished: configuration, intensity of land use, and spatial characteristics referring to diversity, internal continuity and accessibility. These aspects are not necessarily related to one another, and taken separately, may lead to different understanding, definition and measurement of compactness.

A. Configuration — refers to the geometric dimensions like size, shape and spread

5. From the geometric point of view, compactness conforms to a standard dictionary definition quoted by Niemi et al. (1990): "A figure is compact if it is packed into a relatively small space or if its parts are closely packed together. By way of contrast, a figure is not compact to the degree that it is spread out". Thus, circles and squares are considered compact, while long, narrow and 'odd' shapes are thought of as not compact.

6. A great number of configuration measures discussed in the literature are based on geometric figures used as a standard for comparison between different shapes. Numerous standard-free measures of spread or dispersion also exist, based on length to width comparisons, perimeter to area ratio, or center to boundary distances, as well as measures including weighting by population (see Niemi et al. (1990) and Siegel (1996) for a detailed discussion and comparison of different measures). Following Niemi et al. (1990), it is important to note that even solely within the configuration aspect the problem remains multidimensional. No single number can adequately express the two-dimensional quality of space, not speaking about the population or any other additional component, so that no single-variable definition is adequate, and multiple measures should be considered simultaneously in order to define the concept.

7. Configuration measures describe the framework within which the development occurs. But they do not reflect the intensity of the development within a given shape, neither its internal continuity.

B. Intensity of land or space use — refers to the density dimension

8. As note Torrens and Alberti (2000), there is little agreement in the literature about density specification with regards to: what variable (activity) to use – housing units, population, or employment; at which scale to study – metropolitan area, city district, or neighborhood; over which geography to measure – total area (gross density), or area designate for residence (net density).

9. Moreover, there are two broad approaches to measuring density: first, as the absolute amount of space within the total available which is filled by a given land use; second, as the rate at which space is filled with respect to distance from some central point in the city (usually the central business district). The second approach includes calculation of density attenuation based on urban population density functions, and calculation of fractal dimension (see Batty and Kwang (1992) and Mesev et al., (1995) for the detailed discussion).

C. Spatial characteristics of development referring to diversity and dispersion of land use, internal continuity and accessibility

10. Torrens and Alberti (2000) use the term scatter to define such characteristics of non-compact development as fragmentation, leapfrogging, discontinuous, dispersal and piecemeal development. Numerous expressions coming from different fields of knowledge (urban morphology, landscape ecology, spatial interaction theory, information theory, sociology) are used or can be used for measuring spatial characteristics of land use patterns. These expressions may include such variables as density of land use (measured in different ways), number of land uses, distances between zones (defined at different scales) etc., and may take a form of weighted average, correlation coefficient, entropy, and so on. The

following is an attempt to group these measures, taking into account their mathematical form and the field of knowledge where they come from.

(a) Torrens and Alberti (2000) propose an index of scatter calculated as the weighted average distance from residential parcels to their weighted centroid. A concentration measure proposed by SCATTER Project (2002-2004), is based on the similar idea and calculated as the average density of city zones, weighted by the square of distance between the gravity centers of the zones and the whole city. Thinh et al. (2001) imply a degree of compactness indicator for measuring spatial interaction and dispersion of urban settlement structures, inspired by the law of gravitation and calculated as a mean power of attraction between raster cells.

(b) Indicators of spatial association (Morans's I-statistic and others) measure to which extent the space in question is homogeneous or heterogeneous and might be interpreted as measures of scatter of development zones (SCATTER Project, 2002-2004).

(c) Shannon's entropy is used as a measure of spatial concentration and dispersion exhibited by a geographic variable, e.g. density (Yeh and Li, 2001), or as an indicator of land use mix (Allen, 2001).

(d) Measures of diversity and segregation, widely used in demography, sociology and landscape ecology, are applied to measuring different dimensions of non-compact development (Galster et al., 2001; Ewing et al., 2002).

(e) Different accessibility measures are widely used for measuring compactness of urban and rural development (Allen, 2001; Galster et al., 2001; Hasse and Lathrop, 2003).

11. Section 4 presents the specific measures of urban development pattern selected for the present study, based on the considerations of relevance to the project commissioned by the Ministry of the Interior, theoretical advantages of specific measures as proposed in the literature, availability of data and requirements of the factor analysis model used to construct the integrated index of compactness.

12. The project aims to characterize and rank the Israel localities (municipalities and local councils) according to the pattern of the urban area, as far as it is relevant to providing the municipal services to the locality population. These purposes, as well as the data availability, defined the primary set of measures, either selected from the numerous indicators mentioned above or inspired by the ideas met in the literature. This set included configuration measures referring to the size, shape and spread of the urban area, spatial measures referring to its internal concentration, interaction and continuity, as well as population density measures. We focus on patterns of physical entities, such as built-up areas or open spaces, which are distinct from patterns of activity or land use, although related to them. Hence we do not address the questions of accessibility, land use mix or diversity, and do not consider measures based on the population distributions on a detailed scale, such as entropy or density attenuation measures. At this point we focus on the static measures of the development patterns and do not address the dynamic development patterns.

III. Objects of measurement

13. Localities in Israel are divided into two main categories, according to their population size: urban localities are defined as localities with a population of 2,000 or more residents (even if they are of rural type), rural localities are defined as localities with a population of less than 2,000 residents (even if not agricultural). Municipal status of localities is defined in accordance with legislative and administrative regulations, so that

there are three types of local authorities: municipality - consisting of one locality only and authorized as municipality; local council – consisting of one locality only, which has not received the status of a municipality; regional council – including generally a number of rural localities, but may include urban localities as well. The municipal status of localities may change over the years, including the cases of merging of a number of localities into a single municipality or local council.

14. The present study deals with measuring compactness at the level of local authority and addresses the 197 Israel municipalities and local councils, according to their municipal status at the end of 2004. These local authorities include 112 Jewish localities, 72 Arab and Druze localities, and 8 localities with mixed population. There are 4 rural and 193 urban localities (by the population size definition), with a population ranging from 1,291 to 733,329 residents, and the built area ranging from less than 1 square km to more than 80 square km.

15. Following Frenkel and Ashkenazi (2005) who applied a set of available indicators to measuring sprawl in a sample of 78 Israel urban localities with Jewish and mixed population, we defined an **urban built-up area** as an object consisting of the central node and the outlying nodes or nuclei (if they exist). The nodes were defined as follows:

(a) **Central node** is a continuous built-up area within the municipal boundary of an urban locality, which contains most of the residential and other built-up land-uses, as well as inner open land-uses and non-used lands surrounded by the built-up land-uses;

(b) **Outlying node** is a continuous built-up area within the municipal boundary of an urban locality, located separately at a distance from the central node but functionally related to it (i.e. residential districts, industrial zones, institutions etc.). Outlying nodes include inner open land-uses and non-used lands surrounded by the built-up land-uses.

16. The land-use data was obtained from The Land-Use Project 2004 commissioned by the Ministry of Interior and performed by the GIS Department of the Israeli Central Bureau of Statistics, updated for the new construction up to 2006. The built-up land-use categories include buildings for residence, education, health and welfare, public services, culture and leisure, commerce, industry and infrastructure, transportation, and agricultural structures. The latter were not included in the built-up land-uses for the purposes of the present study, and were dealt with in the same way as the open land-uses (public open area, forests, plantations and orchards, cultivated fields) and non-used lands.

17. The Arc GIS 9.3 software was used for the identification of the nodes for each locality. The process was performed by the GIS Department of the Israeli CBS for the purposes of the present study, and included the following steps:

(a) Built-up polygons were surrounded by buffers of 50 m width, to ensure the minimal distance of 100 m between the built-up areas in adjacent nodes (otherwise they add to the same node);

(b) Nodal parts beyond the municipal borders were cut off;

(c) Nodes with an area less than 60,000 square m (60 dunams) were excluded from the urban built-up area;

(d) The node with the maximum area was defined as the central node;

(e) Outlying nodes that have no direct functional linkage with the local authority, and contain solely a quarrying area, a sewage treatment plant, a gas and fuel plant, a water reservoir, or a cemetery, were excluded from the urban built-up area.

18. Few examples of the urban built-up areas defined for the localities are presented in Figure 1 (see page 10).

IV. Applied methodology

19. The Index of Compactness for the set of the 197 localities is computed by means of factor analysis, as a linear combination of indicators selected from the primary set of measures defined under the considerations mentioned in Section 2.

A. Selected measures

20. The final set of indicators was selected subject to the basic requirements of the factor analysis model: balanced coverage of the dimensions under study; sufficient degree of adequacy of the variables for factor analysis; substantial amount of the variance of the compactness measures accounted for by a small number of factors - for greater distinction between the localities. Following these requirements, we avoided inclusion of highly correlated variables characterizing the same dimension, giving a preference to variables with high variance (i.e. considerable differences between the localities). The Kaiser's measure of sampling adequacy calculated both for the entire set of variables and for each variable separately, was used as a basic criterion for an inclusion or elimination of a certain variable. The value of the measure greater than 0.5 (0.73 in our case) indicates, that the entire set of variables belong to the same content sphere. The value of the measure for each variable separately reflects the contribution of the variable to the group in which it is included. The attempt was made to include variables with the measure values greater than 0.5. The final decision was based on the extent to which the variable contributed toward explaining the overall variance as well as how the factors for other variables would be affected if that variable were not included.

21. The following indicators were finally included in the calculation of the index:

(a) Coefficient of variation of radials from the mean radial (following Niemy et al., 1990 and Siegel, 1996):

$$C1 = 100 * \frac{\sqrt{\frac{1}{359}\sum_{i=1}^{360}(r_i - \bar{r})^2}}{\bar{r}} \quad , \quad \bar{r} = \frac{1}{360}\sum_{i=1}^{360} r_i$$

where r_i is the length of the radial passed from the center-point to the boundary of the urban built-up area (i.e. to the most remote point on the boundary of the most outlying node). The center-point is defined as the geometric center of the central node. The radials are spaced at equal angles at the center-point. A circle obtains a zero value, while elongated areas or areas of an irregular shape obtain large values. The values for the localities under study range from to 13.86 to 171.30.

(b) Ratio of the perimeter of the built-up area to the perimeter of the circle with an equal area (Niemy et al., 1990), also called 'shape index':

$L/2\sqrt{\pi S}$ where L and S are the perimeter and the area respectively. The circle is regarded as ideal because it maximizes the area within a given perimeter. The ratio obtains the values from 1 (for a circle) to larger values for areas of an irregular shape. The weighted ratio is calculated for each locality, summing up the shape indices of each node weighted by its relative size:

$$C2 = \sum_{i=1}^{n} \frac{S_i}{S} \frac{L_i}{2\sqrt{\pi S_i}}$$

where n is the whole number of nodes, S_i and S are the areas of node i and the urban built-up area respectively, and L_i is the perimeter of node i. The values obtained for the localities under study range from 1.29 to 5.18.

(c) Percentage of the urban built-up area within the area of the smallest circumscribing polygon:

$$C3 = 100 * \frac{S}{S_p}$$

where S and S_p are the urban built-up area and the area of the smallest circumscribing polygon respectively. The smallest polygon circumscribing all the nodes of the urban built-up area was constructed by the Convex Null function in the Arc GIS 9.3 software. The values of the measure range from 6.10 to 94.76, with lower values reflecting a less compact development.

(d) Percentage of the area of the outlying nodes within the urban built-up area:

$$C4 = 100 * \frac{\sum_{i=1}^{n-1} S_i}{S}$$

where $(n-1)$ is the number of outlying nodes, and S_i and S are the area of outlying node i and the urban built-up area respectively. The values for the localities under study range from 0 to 69.39, where high values reflect a leapfrog development.

(e) Weighted remoteness of outlying nodes, summing up the distances from the boundary of the central node to the boundary of each outlying node weighted by the percentage of its area within the urban built-up area:

$$C5 = \sum_{i=1}^{n-1} 100 * \frac{S_i}{S} d_i$$

where $(n-1)$ is the number of outlying nodes, S_i and S are the area of outlying node i and the built-up area respectively, and d_i is the shortest air distance from the boundary of the central node to the boundary of the outlying node i. The obtained values range from 0 to 322.09, where higher values reflect a less compact development.

(f) Degree of compactness indicator**,** based on the gravitation approach and GIS raster analysis (Thinh et al., 2001):

$$C6 = \frac{1}{0.5h(h-1)} \sum_{i=1}^{h-1} \sum_{j=i+1}^{h} A_{ij} \quad ; \quad A_{ij} = \frac{z_i * z_j}{cd_{ij}^2}$$

where A_{ij} is the reciprocal power of attraction between raster cells i and j computed by analogy with the law of gravitation, z_i is the built area of cell i, d_{ij} is the Eucledian distance between the centers of cells i and j, c is a proportionality factor making A_{ij} non-dimensional (c=100 square m), and h is the total number of all raster cells with a built area greater than 5 square m. The raster network of 100x100 m grid sizes was used for the calculation.

The indicator is viewed as a measure of spatial interaction between area clusters, so that greater values reflect stronger interaction and less dispersion, hence a more compact urban structure. The values obtained for the Israeli localities range from 0.07 to 5.06.

(g) **The overall area of the nodes (the urban built-up area)**, which indicates the overall size of the objects under study:

$$C7 = S$$

The values range from 0.21 to 81.57 square km.

(h) Population density, measured as a number of residents per square km of the urban built-up area:

$$D = \frac{P}{S}$$

where P is the locality population and S is the urban built-up area. The obtained values range from 813 to 22,450 residents per square km, where higher density values refer to a more compact development.

22. The results of the factor analysis and evaluation of rankings of the localities by the index of compactness calculated with and without the population density measure, lead to a decision not to include the population density into the integrated index of compactness, but rather leave it as a separate indicator of an urban development pattern, distinct from the physical structure of the built-up area in a two-dimensional space measured by the rest of the indicators.

B. Integrated Index

23. Two major factors, corresponding to the eigenvalues greater than 1 and explaining 73% of the overall variance, were defined by the factor analysis model based on the z-scores (standardized values) of the seven selected variables. For the sake of convenience, indicators C3 and C6 were multiplied by (-1), so that higher values would indicate a less compact development as do the rest of the measures.

24. The factors (or principal components) are linear combinations of the z-scores of the original variables, where the weights are calculated so as to maximize the differences in the factor values between the investigated units (the urban built-up areas of the localities). The first factor has a maximum power of discrimination between the units. The second factor accounts for the maximum amount of the variance of the original variables not accounted for by the first factor, and so on. The vectors of the weights are orthogonal, so that the factors define an orthogonal set of axes in the multidimensional variable space.

25. An orthogonal rotation of factors is used with the aim to strengthen correlation coefficients between a subset of the original variables and a specific factor. As a result of the rotation, two sets of variables were defined. Variables in the first set have high correlations (above 0.82) with the first factor only and include indicators C1, C3, C4 and C5 (configuration and leapfrog measures). Variables in the second set have high correlations (above 0.73) with the second factor only and include indicators C2, C7 and C6 (measures of shape, size and internal continuity and interaction).

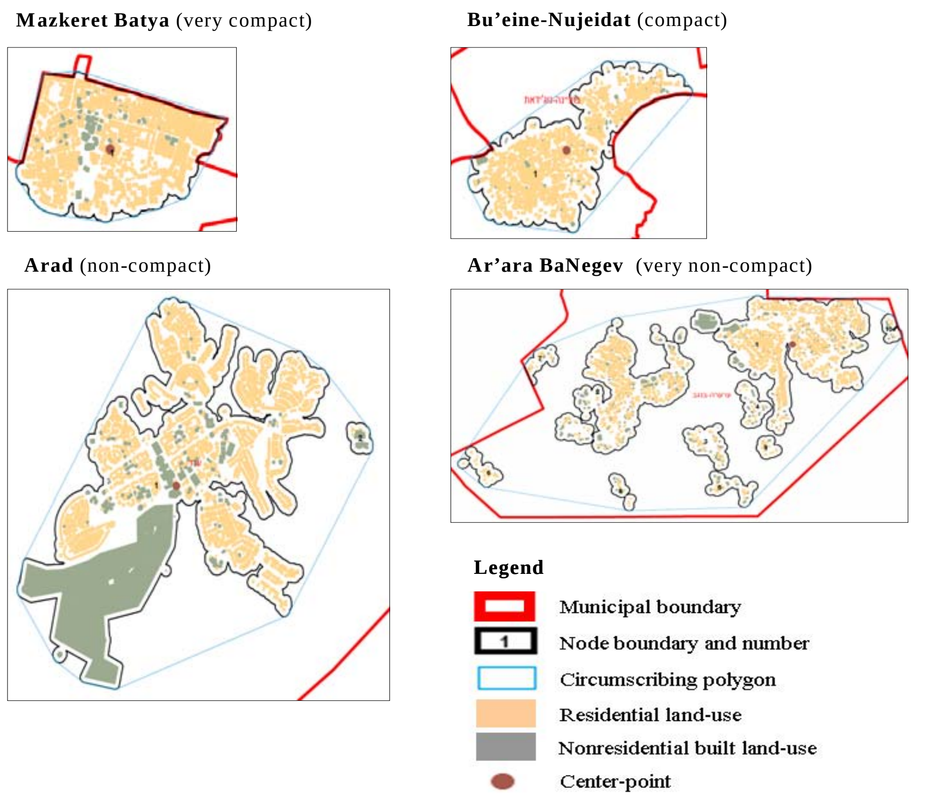
26. The Index of Compactness was calculated as a weighted average of the factor values, where the factors are weighted by the percentage of variance explained by each factor (after the rotation). The index values were normalized to z-scores, ranging from –2.12 to 3.78, with the most compact locality receiving the smallest (and negative) value and the less compact locality receiving the highest (and positive) value.

27. Based on the Index values, the 197 localities were divided into clusters by the Ward's method of cluster analysis. This method uses an analysis of variance approach to evaluate the distances between clusters, so as to minimize within-group differences and to maximize between-group differences. This means that the localities were allocated to clusters, so that the variance of the Index values within the clusters was minimized, and the variance of the Index values between the clusters was maximized. The examples of localities (urban built-up areas) allocated to different clusters of compactness are presented in Figure 1.

V. Conclusions

28. Compactness of an urban area is a multidimensional phenomenon that should be measured by a combination of indicators referring to different dimensions of an urban development pattern. This paper presents the computation of the index of compactness of Israeli municipalities and local councils, aimed to characterize and rank the localities according to the level of compactness of the urban area, as far as it is relevant to providing the municipal services to the locality population. The study focused on measuring patterns of physical entities, such as built-up areas or open spaces. These purposes as well as the data availability and the requirements of the factor analysis procedure, defined the set of measures included in the computation of the index. This set included configuration measures referring to the size, shape and spread of the urban area, as well as spatial measures referring to its internal concentration, interaction and continuity. Population density measure was eventually not included in the integrated index, and considered as a distinct indicator of urban development pattern.

Figure 1
Urban built-up areas of localities allocated to different clusters of compactness (the maps are of various scales)



Locality name	Mazkeret Batya	Bu'eine-Nujeidat	Arad	Ar'ara BaNegev
Population size 2006	8,800	7,853	23,323	12,528
Gross population density (D)	5,232	4,736	3,613	2,785
Urban built-up area, sq km (C7)	1.68	1.66	6.46	4.50
CV of radials (C1)	20.56	43.84	38.04	71.27
Weighted shape index (C2)	1.29	1.99	3.29	2.23
Perc. of built area within the circumscr. polygon (C3)	93.14	72.97	61.70	40.29
Perc. of outlying nodes (C4)	0.00	0.00	1.21	55.43
Weighted remoteness of outlying nodes (C5)	0.00	0.00	0.31	24.34
Degree of compactness indicator (C6)	2.65	1.88	0.70	0.35
Integrated Index of Compactness (based on C1-C7)	-1.60	-0.65	0.31	1.41

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