THE MEASUREMENT OF RESIDENTIAL SPRAWL IN THE JOHANNESBURG METROPOLITAN AREA

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Manuscript accepted April 1991

Residential development in large parts of the Johannesburg metropolitan area is characterized by sprawl conditions. A simulation model was utilized to indicate the extent of future sprawl. Multiple regression and Monte Carlo simulation were used to forecast residential growth to the year 2005. A sprawl index was developed to measure and compare sprawl situations under alternative planning strategies. This index formulates that sprawl is dependent on distance from the built boundary, distance to the dominant work place and dwelling unit density. Simulations show that sprawl will decrease when the overall density is increased, development is concentrated along major transport corridors and incentives are used to attract development to slowly expanding areas.

INTRODUCTION

Sprawl is a phenomenon forming an integral part of the dynamic urban scene and is generally attributed to an inefficient urban structure (Real Estate Research Corporation 1974; Clawson 1962; Harvey and Clark 1965; Gottmann 1967). In South Africa and in the Johannesburg metropolitan area in particular, the authorities' view of sprawl is that it should be avoided. The goals and objectives of the 1985 Strategy Revision and the Land Use-Transportation Structure Plans for the Johannesburg metropolitan area (Johannesburg City Council 1988), the Central Witwatersrand Draft Guide Plan (South Africa (Republic) 1986a:216), and the White Paper on Urbanisation (South Africa (Republic) 1986b:33) all call for compact cities, with higher densities and infilling being encouraged, to offset the environmental, economic and social problems caused by sprawl. Sprawl results in the under-utilisation of land where large tracts between developed areas lie undeveloped and unproductive in anticipation of development. The provision of efficient public transport systems, road networks and social services, and the traversing of long distances between scattered low density development are costly. Sprawl is most noticeable during periods of rapid urban expansion, particularly around the most rapidly growing cities (Harvey and Clark 1965:2). The Johannesburg metropolitan area lies at the core of the most rapidly expanding urban regions of southern Africa, the Pretoria-Witwatersrand-Vereeniging (PWV) region, where 43 percent of the gross geographic product of the Republic is generated (South Africa (Republic) 1981:2). It is in the white residential component of the Johannesburg metropolitan area that the dynamics of sprawl is most prevalent (Sieg 1988).

DEFINITION OF SPRAWL

In the literature concerning the urban fringe and in particular that concerning sprawl, it is seldom satisfactorily defined and is often discussed without a clear frame of reference (Harvey and Clark 1965:1). Sprawl is frequently loosely used to describe a general outward expansion of the city into the transition zone between urban and agricultural land uses (Gottmann 1961; Carver 1962:55). It has more recently been described simply as decentralised settlement (Gordon and Wong 1985:661). Here, however, sprawl is taken to mean more than simply the extension of the outer limits of the city, for it is possible that the outward expansion of the city may take place in an orderly fashion, growing compactly onto the existing fabric. The definition adopted here is based on Harvey and Clark's (1965:2), i.e. sprawl takes the form of non-compact, scattered pockets of urban development which alternate with tracts of undeveloped land. It occurs at some distance from the built-up boundary on the periphery of expanding areas, and has a gross density less than that found in a mature section of the city. Sprawl ranges in size and form from small, isolated pockets of development to large-scale leapfrog development and is also evident in ribbon development along transportation axes.

CAUSES AND EFFECTS OF SPRAWL

One of the major causes of sprawl is an uncoordinated development process, especially where many authorities, land owners and developers are involved. Land speculation is often indicated as a cause, because it results either in land not being made available for development or being prematurely developed. However, according to Harvey and Clark (1965:3) it is not speculation in land *per se* that causes sprawl, but rather the lack of coordination in the speculative market. This together with the unpredictability of the market, may cause developers to allow themselves to be led by rumours and unrealistic expectations. The physical nature of the terrain is also given as a cause, in that land which costs more to develop tends to be developed last. Sprawl is also encouraged by the building of main roads outside the city, which results in ribbon development (Cadwallader, 1985:51-53). An important indirect factor is a planning policy of *laissez faire*. By exercising as little control as possible over the private sector, which in a free-market economy is the major development agent, it is difficult to regulate the activities of township developers effectively.

Sprawl can have various negative effects. Often mentioned are the high costs of transport and services such as water, sewerage and electricity. Where a city is surrounded by high quality agricultural land, the fact that this land is unproductive or swallowed by urban development, is seen in a serious light (Cadwallader, 1985:53-54).

SPRAWL IN THE JOHANNESBURG METROPOLITAN AREA

Since the discovery of gold on the Reef in 1886, Johannesburg has expanded from a compact rectangular shape, measuring 2 kilometres from east to west and 1,5 kilometres from north to south (Hart 1984:53), to a sprawling metropolis with a diameter of approximately 40 kilometres, extending even further in some directions, and an area of about 145 100 ha.

Prior to 1965, except for isolated developments in the south and west of the area, sprawl did not occur to any great extent (Figure 1). Subsequent to this date, however, sprawl became a predominant feature of the rapidly expanding northern and western parts. The boundary of the study area was thus taken to include the rapidly expanding local authorities of Sandton and Randburg; those parts of Johannesburg to the north and north-west; Roodepoort to the west and the 'new south' of Johannesburg. The aim of the study was to determine the present and future extent of sprawl around Johannesburg's core and to assess the effects of alternative planning principles on predicted residential development.

MODELLING SPRAWL

Data concerning the number of dwelling units and distances were collected on a uniform grid basis. An evaluation of the size of all new township developments (applied for in the last five years) in the Johannesburg metropolitan area led to the adoption of a grid size of one square kilometre.

In order to determine the extent of future residential sprawl multiple regression and Monte Carlo simulation (Ayeni 1979:179-187), - standard techniques in a modelling exercise of this kind - were used to predict residential patterns.

In determining the residential location variables to be used in the multiple regression, it was initially decided to treat the entire study area as a whole. Correlations with residential development, were however, poor. An in-depth investigation of the factors which influence residential development indicated that these were diverse and operated differently over the area. In addition, the asymmetrical shape of the area was responsible for anomalous correlations. To offset this the study area was divided into three, as homogeneous as possible, subsystems - SRJ (Sandton, Randburg and northern Johannesburg), RPT (Roodepoort) and JNS (Johannesburg new south).

In order to model residential development using Monte Carlo simulation, it was necessary to determine the probability of development taking place in any given grid cell. Multiple regression was used to obtain a regression coefficient for each independent variable, which gives a measure of their relative importance, thus providing a weighting, which is used in the prediction of future residential development.

The multiple regression was formulated using the least squares estimators of the parameters of a multivariate linear function taking the form of:

$$y = a_o + \Sigma_j a_j x_j$$

where y = number of residential units (dependent variable)

x_j = the jth factor contributing to residential development (independent variable)

a_j = coefficient of the jth factor (a constant)

a_o = intercept of the line on the y axis

The independent variables used in the analysis were drawn from similar studies undertaken by Chapin and Weiss (1968) and Browett (1976) and from the responses to a questionnaire which was sent to planners and engineers operating in the area. Feasibility of measurement was a consideration in the choice of variables. The heterogeneity of the metropolitan area was accounted for by utilising different, applicable variables in each subsystem. Distance to the built boundary as an indicator of service availability, distance to major arterials, proximity to non-white areas and distance to the dominant employment centre (the CBD of Johannesburg), were the variables applicable to all three subsystems. Distance to the nearest railway station was included in the RPT subsystem and in the case of the SRJ subsystem, distances to both the Randburg and Sandton secondary business areas, were used.

FIGURE 1

Residential Development in the Johannesburg Metropolitan area from 1886-1985.

The probabilities obtained from the multiple regression analysis form the basis for Monte Carlo simulation, where residential units are allocated to a grid depending on the probability attached to that grid and depending on whether or not that grid has been chosen by a random number process. A probability matrix is constructed where the attractiveness of each cell is expressed as a portion of the total attractiveness of the entire matrix:

$$p_i = \Sigma_j a_j x_{ij} / \Sigma_i \Sigma_j a_j x_{ij}$$

where p_i = probability of a unit allocated to the ith cell
a_j = coefficient of the jth factor
x_{ij} = value of the jth factor for the ith cell

The probability matrix is transformed into a random number matrix. Random numbers are then drawn and units allocated to the grid in which the random number occurs. The inclusion of the random element accounts for the random nature of the decision-making process in residential location and compensates to some extent for independent variables not included in the multiple regression. Allocation continues until the total number of projected units has been allocated and the set limit is reached. The capacity for the initial run was set at 700 units per 1 kilometer squared grid, which, allowing 30 percent of the land for roads, schools, shops and other services and amenities, resulted in an average stand size of about 1000 square metres. This corresponded to the average size for peripheral developments in the study area. This grid capacity was adjusted, however, for different runs when the effect of certain density policies on sprawl was tested.

The simulation was initially carried out for the period 1966 to 1985 and compared with observed development for that period to test the accuracy of the model. The results were statistically tested and were found to be comparable with other studies. The model was accepted and was used to predict residential development to the year 2005.

QUANTIFICATION OF SPRAWL: THE SPRAWL INDEX

Although sprawl has been discussed and analysed in varying degrees, no evidence was found of any attempt to quantify sprawl with a view to comparing sprawl situations in different areas or under different conditions. Apart from the attempt at attaching an economic and social cost to sprawl (Real Estate Research Corporation 1974), discussion regarding sprawl has tended to be descriptive, subjective and emotional. Although it is possible to visually assess, to a certain extent, the amount of residential sprawl occurring at any one time from aerial photographs and maps, this becomes more difficult when overall sprawl patterns are compared over different time periods and under different planning policies. It was therefore considered necessary to formulate a more exact measure of sprawl, not as a definitive measure of sprawl, but one which would nevertheless facilitate the comparison of residential sprawl situations.

A simple sprawl index was developed using three variables - distance to the built boundary, distance to the dominant employment centre and dwelling unit density. The sprawl index takes the form of:

$$S = \Sigma rcd / 10^{-6}$$

where S = sprawl index
r = distance in metres from built boundary to the centre of a grid
d = density (number of dwelling units per grid)
c = distance to the dominant employment centre from the centre of a grid

A product moment form was utilised because in measuring the sprawl distribution of a quantity, moment measures are commonly found to be useful. The measure of dispersion is rc while the intensity measure is d. A further reason for utilising this form was to allow S to be zero when d is zero because if no units occur in a grid, the sprawl index is expected to be zero. The only instance where zero units in a grid contribute to sprawl is when an empty grid occurs between other developed grids resulting in leap-frog development. While this occurrence is found in existing development, simulated development allocates continuously and thus this situation does not apply in the present study. Although a grid may be immediately adjacent to the built boundary, r is never equal to zero because the measurement is made to the centre of the grid. Division by 10^{-6} was simply to facilitate manageable numbers.

Distance from built boundary (r)

Sprawl is directly proportional to the distance from the built boundary. Sprawl increases as this distance increases. For the 1966 to 1985 sprawl index, the 1965 built boundary was used, whereas for future predictions the 1985 built boundary was used. The closer any development is to the built boundary, the easier and less costly it is to provide services and public transport and the more accessible it is to already existing schools, shopping centres and other community amenities. It seems obvious that the most effective way for a city to grow is to add on in a compact manner to the existing compact form. The further development occurs from the built boundary, the more area must be traversed in terms of the provision of services and in terms of travel time, resulting in an inefficient urban system.

Distance to the dominant employment centre (c)

The home-to-work trip distance, in the index represented by distance to dominant employment centre, is perhaps the most important concern of sprawl development. The problem is not only unique to the type of sprawl defined for the purpose of the study, but generally to any outwardly expanding metropolis. The development could be compact and continuous yet still involve the problem of increasing home-to-work trip distances. Sprawl, as defined in this study does, however, exacerbate the problem in that open areas must be traversed unnecessarily. One way of reducing the home-to-work trip distance in terms of the index would be to locate new secondary employment centres in outlying areas.

Dwelling unit density (d)

For the purpose of the sprawl index, the relationship between dwelling density and sprawl is proportional with fewer units associated with less sprawl and more units with greater sprawl. This is based on the premise that a small sprawl development, in terms of scale, would mean a smaller problem, with less total time and cost being expended on the journey to work and other amenities. The time period over which the sprawl is measured would thus have an influence on the sprawl index with shorter periods resulting in a lower index due to fewer units being added. This would need to be borne in mind when comparing the index when unequal time periods are used.

An alternative opposite premise could be used if it is argued that it is more cost effective to provide engineering, telecommunication and public transport services to more units. The negative distance effects of the sprawl would thus be offset by the large demand for the services. In addition, the larger the community, the more worthwhile it becomes for the developer to provide amenities such as schools and shops within the new development, reducing the dependence on facilities within the built boundary. Interaction between the core and the sprawl development is thus largely limited to the home-to-work trip, which remains the crucial problem. Even though the number of trips may be reduced by the provision of amenities within the sprawl development, the vast majority of trips must be made in the form of the daily home-to-work trip. The argument then reverts to the original premise that the more people living in the sprawl development, the more time, fuel and effort will be expended unnecessarily.

In accordance with the present definition of sprawl it was desired that distance to nearest development also be included in the formula in order to measure any leap-frog development. The manner in which the simulation occurs, however, results in largely continuous residential development, with the effect that distances between developments are zero. Even if this measurement could have been made, no leap-frog development of less than 1 kilometre apart would have been picked up due to the grid size. It was decided that a measure of leap-frog development could be obtained in a density measure where very low densities could be associated with scattered development.

SIMULATED RESIDENTIAL DEVELOPMENT UNDER VARIOUS PLANNING POLICIES

The main purpose of predicting residential development was to enable the testing of the effects of alternative planning strategies, largely density orientated, on the sprawl situation. Although the effects of changes in policy are often logically predictable it is very useful in convincing both politicians and the public of the effects of certain strategies if a proven spatial pattern and index values are available for study and comparison purposes.

The following planning alternatives to reduce sprawl were examined:

1. *Overall density increase:* The most obvious way to reduce urban sprawl is to increase densities. This can be done to a limited extent by subdivisions, second dwellings and renewal within the existing fabric of the city. The most effective way, though, would be to increase the minimum density requirement in new developing areas. The 1985 and the future residential development predictions for 1995 and 2005 were initially carried out with a general maximum capacity of 700 units per grid, which on the ground relates to an average stand of 1000 square metres – the average stand size of presently developing townships in the areas under consideration. An overall density increase of 43 percent was then introduced to observe the effect of a uniform density increase on the sprawl situation. This resulted in a general capacity of 1000 units per grid which relates on the ground to an effective stand size of 700 square metres.
2. *Density increase in specific areas:* In the case of concentrated high density developments and the consequent burden on services, it makes planning sense to locate these higher densities at specific locations where facilities are specially organised to cope with the increase in the most cost effective way. The most logical way to implement this is to link in close proximity in space the work place, the route to work and higher residential densities. For this reason it is proposed that higher densities be located along transportation corridors linking work places. The dominant transportation corridor in the Johannesburg metropolitan area is its northern corridor and it is along the two major roads of this corridor in the SRJ subsystem that higher densities are desirable. A major factor in the success of locating higher densities along major transport corridors is that public transport would be the major mode of travel. Failing this these routes would become overcongested. No transportation corridor has yet emerged in the JNS subsystem but in the RPT subsystem an attempt was made to increase densities in grids within walking distance of railway stations, with the railway line being identified as the transportation corridor.
3. *Growth incentives in slowly expanding areas:* The number of units allocated between 1966 and 1985 and the predicted number of units allocated for the year 2005 to the JNS subsystem, has increased and is expected to grow very slowly in comparison to the other two subsystems. On the other hand, the SRJ grew 75 per cent more than the RPT subsystem and 230 per cent more than the JNS subsystem during the period 1966 to 1985 and is expected to grow 70 per cent more than the RPT subsystem and 270 percent more than the JNS subsystem in the next 20 years. Notwithstanding the larger size of the SRJ subsystem, the growth imbalance is clear and with the Johannesburg CBD remaining the dominant work place for all subsystems, an overall inefficient urban system results from the imbalance. This creates unnecessary overcapacity problems in the north which are likely to worsen in the future. A possible solution would be to encourage growth in the JNS subsystem and discourage growth in the SRJ subsystem. The result of increasing the JNS subsystem by 9000 units and depleting the SRJ subsystem by the same amount, was tested by the simulation model and the effects on the sprawl index determined.

SIMULATION AND SPRAWL INDEX RESULTS

A cursory visual assessment of the predicted residential development patterns obtained under various planning alternatives was made, although only very general trends could be observed from the map forms. It is in the comparison and investigation of the sprawl index in the various situations, that more rigorous conclusions about the future development pattern can be drawn. The average sprawl index for each subsystem under the various conditions was calculated to facilitate comparison between the different sized subsystems and in the case of the SRJ subsystem, between the development with certain outer grids excluded (1985) and included (2005).

It was possible to validate the sprawl index to a certain extent by applying the index to both the 1985 observed and predicted development (Table 1). Similar results were obtained. This indicates that even though patterns may differ in the future from the simulated pattern, if the exogenously determined unit allocation totals are close to reality, the sprawl index will remain a good indicator of the amount of sprawl which can be expected in the future. Of the three subsystems, the RPT subsystem exhibited the greatest average sprawl between 1966 and 1985 while the JNS subsystem experienced the least. A visual interpretation indicates in the case of the RPT subsystem, that the most likely reason for this high sprawl index is the occurrence of high densities at distances far removed from the built boundary (Figure 2a). In the case of the simulated development for 1985 in the RPT subsystem, the index was increased to a similar amount as the 1985 observed amount by the allocation of small densities to the grids in the northern central area of Roodepoort which in the observed case exhibited no sprawl (Figure 2b). The major reason for the higher sprawl index in the case of the SRJ subsystem 1985 predicted situation is that units were allocated to outer zones which in the observed case were empty. The fact that in the JNS subsystem, the 1985 predicted index was marginally lower than that for the observed case, can be attributed to the undersimulation of actual sprawl development in the extreme south of the JNS subsystem.

TABLE 1: The sprawl index for different years and for various planning policies in each subsystem.

	RPT*		SRJ**		JNS***	
	Total	Average	Total	Average	Total	Average
1985 observed	174	2,12	195	1,36	51	0,65
1985 predicted	173	2,11	210	1,47	48	0,61
2005 @ 700 (low density)	63	0,77	312	1,90	63	0,79
2005 @ 1000 (medium density)	46	0,56	259	1,58	58	0,74
2005 adjusted	-	-	247	1,50	106	1,34
2005 added	64	0,77	275	1,68	-	-

Average = Total ÷ number of grids
* Roodepoort
** Sandton/Randburg/northern Johannesburg
*** Johannesburg new south

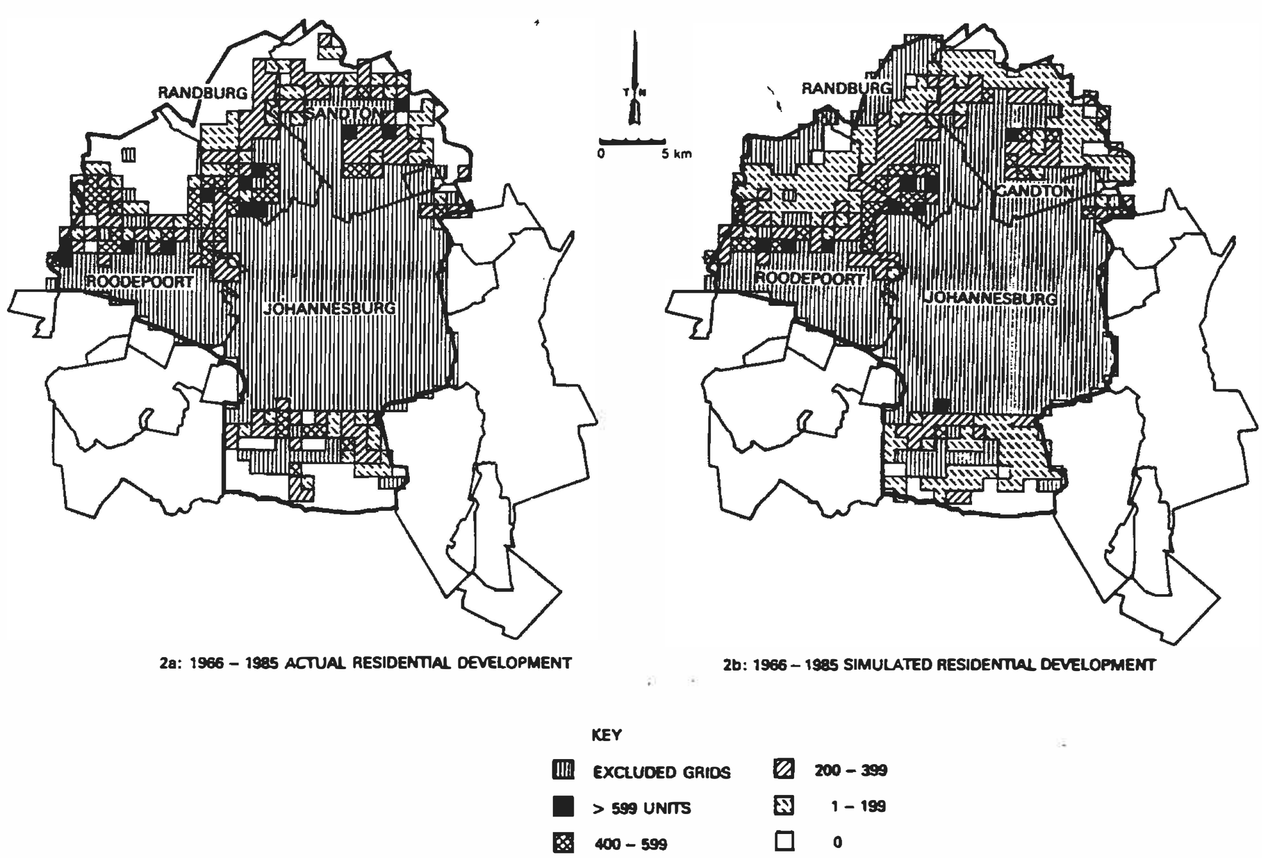

FIGURE 2

Actual and simulated residential development in the Johannesburg metropolitan area from 1966–1985.

The 2005 sprawl situation at a capacity of 700 units per grid (low density) is worse than the 1985 sprawl for both the SRJ and JNS subsystems (Table 1). The highest sprawl occurs in the SRJ subsystem. Increasing the capacity to 1000 units per grid (medium density) resulted in an expected decrease in the sprawl index of all three subsystems (Table 1). The main reason for this decrease was not as a result of no units being allocated to more grids in the outlying areas but rather the outlying grids were allocated few units while the grids close to the built boundary were allocated an increased number of units.

This is obvious from a study of individual grid allocations. The reason for the SRJ subsystem giving consistently high sprawl indices can partly be attributed to the value obtained by multiplying the average distance to the 1985 built boundary and distance to the CBD. Although the SRJ subsystem obtains the intermediate average value of these two distances in comparison to the other two subsystems, the multiplication of the two distances, gives the highest value of all subsystems. Sprawl is reduced the most in the SRJ subsystem when the capacity is increased to 1000 units per grid (medium density) in absolute terms but in relative terms the greatest percentage decrease in sprawl was experienced by the RPT subsystem (Table 1). A visual perusal and comparison of the 2005 simulated development for both capacities indicate that part of the reason can be attributed to fewer units being allocated to more of the grids in the northern central region for the 1000 units per grid capacity (Figures 3a and 3b).

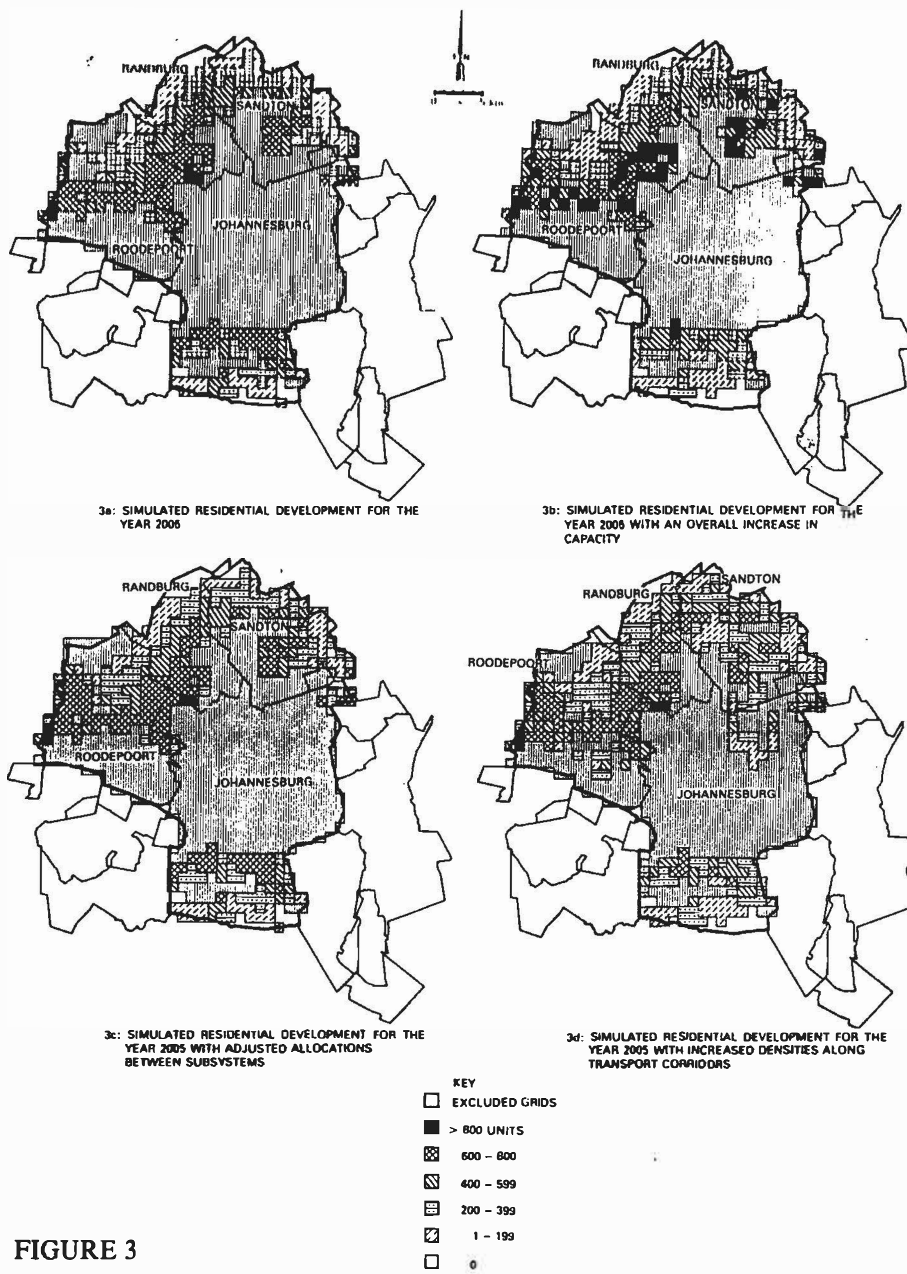

FIGURE 3

Effect of various planning policies on residential development in the Johannesburg metropolitan area for the year 2005.

It is evident from the above that the SRJ subsystem is predicted to experience the most sprawl of all three subsystems by the year 2005. By adjusting the portion of the total allocation to decrease the amount allocated to the SRJ subsystem and to increase the amount going to the JNS subsystem, the average SRJ subsystem sprawl index (2005 adjusted) decreases by 5 percent from the 2005 index at 1000 unit capacity and by 21 percent from the 2005 index at 700 unit capacity (Table 1). A visual assessment indicates residential growth extending almost to the southern boundary of the JNS subsystem, which nevertheless remains closer to the dominant employment centre than development along the north-western boundary (Figure 3c). The 2005 adjusted simulation is carried out at a 700 unit capacity. The sprawl index of the JNS subsystem accordingly increases but is still lower than the SRJ subsystem adjusted figure and thus for the system as a whole it can be taken as an improvement.

The final policy change which was tested was the increasing of densities along major transport corridors for both the RPT and SRJ subsystems. For this purpose some of the grids previously excluded from the study, as they occurred in the already built-up portion of the city, were opened up for higher densities. This was only done for the purpose of this final test and was not included in the sprawl index as it was the effect on the peripheral development which was desired to be tested. In the case of the SRJ subsystem, the sprawl index (2005 adjusted) showed a decrease, as expected, of 12 per cent from the 2005 prediction at 700 units per grid capacity but no change occurred in the RPT subsystem. A perusal of the relevant map indicates, as expected, fewer units in the furthest grids in the SRJ subsystem as expected (Figure 3d). The reason for no change in the index of the RPT subsystem can be attributed to the more distant, northerly areas in the 2005 added situation while other central northern cells were allocated fewer units than before resulting in an averaging out effect (Figure 3d).

EVALUATION

The major limitation of measuring sprawl from the simulated residential development is that the leap-frog type sprawl cannot be directly measured. It was initially thought that the long time period used, i.e. 20 years, was partly responsible for this shortcoming, as sprawl situations of the leap-frog type have a tendency to become absorbed into the main fabric or built boundary of the urban form with time. The performance of the simulation allocation over a shorter, two year time period was tested in the SRJ subsystem. Two noticeable features relating to the sprawl pattern emerged. The influence of the development prior to 1985 and secondly the manner in which the allocation process occurred – which was to allocate at first fairly uniformly over the study area, except for exceedingly far out grids – together, resulted in very few empty grids occurring between developed grids, although more were observed than had occurred in the 2005 picture.

A further final consideration of the sprawl index is its dependence on distance to built boundary. For all the future predictions, distance to the 1985 built boundary was used whereas in actual fact the built boundary expands as the city grows and thus is constantly changing. This would probably result in lower indices as the distance to the existing grids decreases. Again it must be stressed that the purpose of the index was not to obtain an absolute value of the sprawl index but rather to facilitate comparisons. As long as the built boundary remains constant in comparative situations, whether it be further away or closer, the index remains a useful planning tool.

RECOMMENDATIONS

Although the index is useful for comparison purposes, it could be much more meaningful if the actual numerical value gave an indication of the cost of sprawl. An extremely valuable measure would be sprawl limits beyond which the index would reveal sprawl as being unacceptable in terms of the cost to the individual and to the local authority, below which the sprawl could be taken to be insignificant in terms of energy utilisation and inefficiency, and between which sprawl would be acceptable. A determination of the costs involved in sprawl would need to include a weighting of the cost to the individual in terms of travel time with its associated monetary costs of fuel or bus/rail tickets as opposed to the relative monetary gain of locating at further distances in terms of cheaper land prices. The cost to the local authority would have to be calculated taking into account the cost of providing essential services, public transport and additional roads as opposed to the increased revenue of an expanded urban area.

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