Experiments with Settlement Aggregation Models

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0 Abstract

The use of fractal techniques to model aspects of urban form is now well established. However, to date these have concentrated on specific general attributes of urban form, usually focused at a macro level. This paper argues that the urban system is complex and its global spatial attributes related to patterns of activity and movement at the local scale. In order to arrive at a generative model which simulates the pattern of urban development, two interrelated urban spatial systems need to be modelled together. These are the built form system which reflects the pattern of uses and activities associated with the use of particular spaces and the movement system that connects those spaces. This paper describes early experiments in spatial modelling which attempt to combine aspects of the two systems in the understanding of the development of informal settlements and low income housing in developing countries.

1 Introduction

Recent advances in the scientific understanding of complex phenomena and the vast increase in the availability of cheap computing power which has helped facilitate this understanding have provided urban theorists with a whole range of new tools for analysing and modelling urban systems. However, most urban modelling applications have failed to come to terms with the geographical complexity of real cities. Models remain abstract and idealised, focused at a macro scale or on a limited descriptive analysis of particular attributes of the urban system. Given the capacity of generative modelling techniques for simulating dynamic interactive systems, why has this potential not been fully utilised in the modelling of cities? This has much to do with the shear complexity of cities as social, cultural and economic phenomena. However, our experiments suggest that many aspects of urban form are open to rule-based generative descriptions. We believe that considerable progress can be made if generative, computer-based methods are linked with an analytical approach which draws on established studies in the morphogenesis of cities and of urban settlements as socio-cultural phenomena.

To construct a generative model which simulates the spatial pattern of urban development, two interrelated urban spatial systems need to be modelled together. These are the built form system which reflects the pattern of uses and activities associated with the use of particular spaces and the movement system that connects those spaces. This paper describes early experiments in spatial modelling which attempt to combine aspects of these two systems in the understanding of the development of informal settlements and low income housing in developing countries. The intention of this work is practical, aiming to translate a theoretical understanding of urban form development patterns into new, accessible planning tools for dealing with rapid urbanisation. At the same time, this practical focus offers the opportunity to explore the dynamic complexity of urban spatial relationships in the context of various types of informal settlement. Such settlements often function quite successfully at a global scale, although their overall form is a cumulative effect of a multitude small scale, uncoordinated localised decisions relating to social, economic and environmental conditions.

The history of urban modelling at the macro scale has seen a movement from simple, single theory-based techniques (gravity models, random utility models, etc.) to those that draw on a variety of theoretical viewpoints (Wegener, 1994) to represent different components of the development process. In a similar way but at a local scale, we have viewed urban development as a series of related processes which requires a suite of models. These can be used as stand-alone techniques or in combinations with one another. Essentially, these techniques model the local aggregative process of urban form development. This involves mapping dynamic spatial relationships at an elemental level of building to building or building to public street space and modelling the cumulative affects of these simple relationships. The model uses a rule-based aggregative procedure which is intended to represent, albeit at this stage in a simplified form, social codes that operate in the "'real world'" of urban development.

The paper includes a discussion of the issues of settlement form and morphological theory and a brief review of the previous use of fractal modellers, cellular automata and aggregative techniques in the modelling of urban spatial phenomena. This provides the context for the discussion of the authors' experimental work with dynamic morphological techniques. Three prototype models, dealing with different aspects of settlement and house development and broadly based on observed built form, are described and their generative procedures outlined. A brief description of the use of the programming approach using standard CAD software is described below. (included in the appendix).

The development of cities can be seen as the result of two interactive processes. One involves formal planning and urban design, the other results from a series of independent actions by individual developers. The former is informed by a global overview and involves strategically informed interventions. The latter are largely local in character and, while cumulatively these actions may shape the physical urban pattern, they are not usually motivated by a concern for the city as a whole. Whereas buildings are usually designed by an individual or a small team of people, cities seldom are. Cities tend to grow and change as the result of the multitude of localised actions at a variety of scales.

In some cases, such actions are restricted by planning controls, but this is not always the case. In places where urban development is uncontrolled, it often results in settlements that are said to be 'organic' in form. Such a settlement form is not constrained by an overall design or master plan but is still the result of a rational decision-making process. This process, however, operates at the local level as individual developers seek to maximise the utility of each site, within the local physical constraints and according to established social practice. The form that emerges from this process is often striking, especially where the rules for its generation are strongly localised and the units of development similar to one another. Commonly this is exhibited in areas of housing, where social units are distinct but similar spatial requirements and established building technology tend to produce buildings of a similar form.

The aim of our research is to develop modelling techniques which can demonstrate how patterns of movement, informal social codes or formal local planning codes and interventions can affect the wider physical form of settlement. These models are seen primarily not as predictive but rather as illustrative tools for understanding the process of urban development and the influences upon it. They may be used to explore the emergent properties of different types of urban settlement and to suggest ways in which planners could have a beneficial influence on the development processes otherwise beyond their control.

In all settlements a degree of overall planning is desirable, particularly as they grow larger. Transport and other service infrastructures need to be planned if they are to work efficiently. Likewise, the nature and location of social amenities need to be considered in relation to the overall city if they are to be of optimum use to its inhabitants. Planning interventions need to be evaluated in terms of achieving the maximum public benefit with the minimum input of resources. Techniques for exploring the knock-on effects and counter-intuitive consequences of such interventions are therefore vital. These, then, require a planning process that allows an evaluation of, and can respond to, the overall pattern of the city.

2 Issues of settlement form

The organic form of unplanned settlements may sometimes appear chaotic but it has also been much admired by architects and urban designers and provided inspiration as a model for new urban development. The history of urban design is filled with the echoes of Mediterranean hill towns, or English villages. This is based on an aesthetic and visual appreciation of the built form, rather than on an analysis of the structure of socio-spatial relationships which underpin the physical arrangement of spaces. The aesthetic of the picturesque has a long tradition in urban design in the ideas and work of Sitte, Parker and Unwin, Cullen, Spoerry and others (Broadbent 1990, pp 211-233). As a basis for urban restructuring, it has not been without problems - especially where a particular model, say a Greek village, has been adapted and transplanted to a new cultural setting such as a London housing estate (Hillier and Hanson 1984, p 132).

Parallel with this picturesque tendency in urban design many town planners, from Patrick Geddes onwards, have described the city as an organism, characterised by irregular patterns which result from slow accumulation of change and incremental growth (Lynch 1987, pp 88-98; Kostof 1991 pp 43-45). The idea of small incremental change has been a reoccurring theme in the work of Christopher Alexander, one of the few urban theorists who has explored the activity characteristics underlying traditional, organic types of settlement. Alexander's theories began from a functionalist perspective in his early work, Notes on the Synthesis of Form (1964), relating place to human activity using the formal theory of sets. Later he developed the Pattern Language (Alexander, 1979) which was an attempt to catalogue in a set of maxims a set of place-making behaviour patterns and activities which could inform the building and urban design process. More recently, the concept of incremental growth is one of the seven guiding principles of a holistic theory of urban design (Alexander, 1987).

Spiro Kostof (1991, 1992) illustrates in some detail the social processes which underlie the historical development of urban settlement patterns. He deals with both informal, organic urban forms, and the more regular forms based on grids or other formal geometries. Kostof describes most cities as being the product of both planned and

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unplanned processes. He gives the example of a Roman settlement, based on a regular grid, which has gradually broken down and taken on an irregular form in response to social changes in the subsequent mediaeval and Islamic epochs (Kostof 1991, p 49). By contrast, in the upgrading of modern squatter settlements a regular street pattern is often imposed on an urban form that has grown organically, and incrementally, exactly in the manner of mediaeval hill towns or Islamic settlements.

The idea that modern squatter settlements are a form of vernacular is a theme that has been fruitfully explored by that school of theorists, of whom Paul Oliver and Amos Rapoport are perhaps the most well known, who have adopted an anthropological and socio-cultural perspective on architecture and urban design (see, for example, Saglamer and Erdogan, 1993). This was associated with the view of John Turner and others that the squatter settlement frequently represented a functional adaptation to the needs of its inhabitants. Although this outlook radically affected the planning approach to low income housing in the seventies, the conventional view continues to lay stress on the social problems associated with such settlements and to emphasise their temporary character. In practice, however, they are frequently upgraded and consolidated until they become hardly distinguishable from any other district of a city (Kostof, 1991, p 68; Caminos & Goethert, 1978, p 207).

Beneath the apparent chaos of the modern squatter settlement there is often a clear consistency of form and urban structure which varies from place to place. Such consistencies derive at the local level from the relationship between urban form and social processes. Local spatial customs and unwritten social codes determine the layout, spacing and growth of houses and the development of plots and settlement form. Housing and settlement typologies reflect both socio-economic and cultural constraints on who lives where and how they live.

This concept of the informal pattern produced by a social process has a major importance in the world today because of the unprecedented growth of the urban population in developing countries, most of which have this type of informal character. Two-thirds of the total growth in world population between 1950 and 2000 will have taken place in cities of the developing world (United Nations Centre for Human Settlements, 1987, p 23). Between 30 and 60% of the population of those cities live in illegally developed neighbourhoods. In most cities 70 to 95% of all new housing is 'informal', that is built on squatted or, more commonly, on illegally sub-divided private plots. With urban poverty set to become the most significant global issue in the coming century and with traditional approaches to town planning having proved ineffective in dealing with the associated problems, rapid urbanisation in developing countries is demanding new strategies and new tools for urban planning and management.

One way of dealing with the problems associated with rapid urbanisation in developing countries is to better understand the process of informal urban development so that scarce resources can be utilised more efficiently. An area of particular interest is the potential effect, in terms of settlement form, of planned decisions about transport and services infrastructure on adjacent unserviced informal development. The cost of infrastructure provision tends to vary with the size and layout of the urban block (Caminos & Goethert, 1978, pp 146-163). With informal settlements, this depends on the initial conditions and the 'rules' by which an informal settlement is generated. By predicting likely settlement characteristics, modelling techniques can help inform policy towards informal settlements and their future upgrading. Another use of this type of modelling would be to explore the effects of the imposition of different types of building development code, given varying conditions of local enforcement and institutional development. 11.5

3 Scale, area and morphological units in urban analysis

Some authors (Kostof, 1991, p 43; Batty and Longley, 1994, p 28) distinguish between the planned and the 'organic'. Others use the term unplanned (Schaur, 1992, p 16). Whatever the terminology used, this distinction in urban morphology is problematic. While most urban development lacks a controlling master plan, in almost all cases city form is a result of rational decisions and inventive imagination. However, the people who make these decisions may be working at a variety of scales, from the total urban system down to the small local scale, such as an extension to an existing house.

Cities designed as a total entity are an exception. Some urban subsystems, such as service utilities, may be managed as a single unit but even these tend to be constructed in phases. Cities are developed in discrete parcels of varying size and the urban pattern depends on the scale at which it is being viewed. Many large sites in a city may be regularly laid out at a local level but form fragments of an irregular urban mosaic at a large scale. The estate or subdivision are common, as is development associated with particular artefacts such as ribbon development along arterial roads. To a degree, these parcels can be studied in isolation as they frequently have a consistent morphology and a more or less formal structure. It is therefore more useful to identify the scale and areas at which design decisions are made rather than to use the terms organic and planned in relation to urban form.

A substantial methodology has developed in analysing the morphology of settlement patterns, in particular based on the work of M.R.G. Conzen (Lane, 1993; Slater, 1990). Phases of urban development are dictated by economic and social forces and, in examining the historic development of urban form, one can identify distinct periods related to those forces. These Conzen describes as morphological periods (Conzen, 1969, p 7). In such periods the type of development and the forces which produce it have a degree of consistency, producing a distinctive and homogeneous material form. Such areas are identifiable in space as well as in time and the pattern of urban growth can likewise be divided into plan-units or plan-regions (Conzen, 1969, p 5 and p 128).

While the scale and extent of conscious planning may vary from area to area, collections of such plan areas are frequently associated within a broad phase of urban development in the history of a city and may thus relate to a particular morphological period. Areas of concurrent development within the same period may include, for example, the formal subdivision of a large site, informal development along an existing road, or the clustering of development around a nodal amenity. While they may have been designed largely independently of one another, such areas do not act as autonomous units in the city. Each will be influenced not only by the spatial constraints of its immediate location, but also its location in the movement network of the settlement as a whole.

To understand urban morphology we need to identify the range of influences and development pressures which occur in the same place and in the same period but which result in a variety of forms. Rather than develop a single model which describes the urban form of a whole city, we see the need to develop models which simulate local processes and their cumulative effects on global structure.

4 Movement and activity - core and periphery

Activity within the urban system is governed by what Hillier and Penn (1993) describe as a ‘movement economy’. They refer to the city as a physical system consisting of two components - a continuous network of spaces and a collection of functional locations associated with particular land uses. The city can thus be described as a product of the two spatial systems:

-1 A series of discrete spaces associated with a particular ownership and use or set of uses. These we refer to simply as buildings, though they may include outdoor spaces with specific functions.
-2 A network enabling movement and access which supports and connects buildings. We shall refer to this as the street network although, in some cases, this may also include non-street based forms of transportation such a urban rail systems.

Any movement within the network is between a pair of functional locations and the total movement will be a function not only of the total amount of origins and destinations but of the configuration of the system and the manner in which it facilitates movement. The distribution of functions will change over time but is influenced by the physical configuration of the street network.

Authors on urban morphology recognise that one of the most enduring artefacts of the city is the pattern of the street network (Rossi 1982, p 52; Conzen, 1969, p 5). Despite this, most concentrate on the form of buildings and collections of buildings that make up urban blocks. However, the same building may have several uses and many occupancies, and the same plot may be occupied by numerous buildings over time (Conzen, 1969, p 94). What tends to remain consistent is the relationship between plot and street. Plots, on occasion, are amalgamated or subdivided, especially when uses change. However, this tends to happen within the context of existing street patterns (Conzen, 1990). Perhaps more common is the adaptive re-use of existing buildings for a different function. Given the dynamic nature of the movement economy and relatively fixed nature of the street network, shifts in building use become the main mechanism of change in the urban system and this is reflected in fluctuations in and variations between property prices.

We can identify two phases of urban development. In the first, the street pattern and the functional distribution of buildings are laid down together, the distribution of each influencing the development of the other. The second, mature phase is characterised by a more stable structure and a dynamic process whereby the distribution of uses continues to shift with only minor modifications to the physical structure. As cities expand, a ring characterised by the initial phase surrounds a core characterised by the latter. These two zones tend to have a different urban structure (White and Engelen 1993,).

While the movement system appears to be the most important component in the development of the city, it is the most difficult to adapt. As cities grow it becomes necessary to increase the capacity of the street network. Radical restructuring, such as that of 19th century Paris, is rare. An alternative is the complete replacement of the functional core of the city by another at a larger scale, such as the Cerda grid area in Barcelona. A common response is the augmentation of the system by additional movement infrastructure, such as transit systems.

The developing fringe provides an opportunity to compensate for structural obsolescence in the centre, the ring road and the by-pass being common responses. A consistent aspect on the mature structure of the city is the minor improvements which increase the efficiency of the network, such as the widening of existing roads. These 'improvements' to the structure of cities, are attempts to maintain the economic activity of the city and protect the investment vested in the existing building stock. Such structural adjustments are a localised response to the global dynamic state of the system and to shifts in the movement economy of the city.

The structure of the developing peripheral urban ring will be constrained by existing local artefacts of the core - new streets must be connected to existing ones, for example. Other cultural, social and economic factors will obviously have an influence. The value of land and existing patterns of ownership and tenure will affect the subsequent urban development. The development pattern of many European cities can be traced to that of the fields on which they were built (Rossi, 1984, p 152). Further, movement between settlements will create an external movement economy shaping the internal pattern of development. It gives rise to a characteristic ribbon development along existing roads and the development of principle streets in many European cities on the route of the original ancient roads which linked their nascent centres to the outside world.

There is by now, of course, an established tradition of computer modelling of the movement economy. Conventionally, models of urban movement and land use activity have developed from the concept of dividing the city into functional spatial zones and examining the flows generated between them through trip distribution and modal split models (Lloyd-Jones and Erickson, 1996). Although not initially successful in providing insight into the interaction of place, form and transport in cities, such models have subsequently reached a high level of sophistication, both on the trip generation, demand side and on the supply side in terms of accounting for floor space and transport infrastructure utilisation (see, for example, Williams, 1994).

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While the various modelling approaches currently in use have a substantial economic content, they tend to be highly aggregated and/or treat the behaviour of people in cities solely in utility-maximising terms. This is unsatisfactory in explaining the actual determinants of activity at the local scale and the influence of socio-cultural factors or existing built form (both 'buildings' and 'streets'). There is a need, therefore, to relate this type of urban systems modelling to more spatially-specific models which demonstrate how urban form develops as a unit of development. In order to be useful, a model of urban form needs to simulate the spatial form of the city and the process by which it is laid down. Three central tasks for a developmental model of urban morphology present themselves:

-1 Modelling the development of built form.
-2 Modelling the evolution of street system and the distribution of activities (immature phase).
-3 Modelling the structural adjustment to global shifts in the dynamic urban frame work (mature phase).

Such a model should not only be able to simulate the cumulative effects of localised socio-spatial events but should also include a mechanism whereby the global state of the system can feedback into the local development process.

Settlements almost always develop in the context of existing cultural artefacts - roads, agricultural and other property divisions, etc. - and all urban development is influenced by the external movement economy. In this respect it is useful to consider all urban development as being a form of transition or extension rather than as autonomous. The initial state of any generative model will have a significant impact on its final form. A model of urban development needs to include these 'seed' structures. The existence of an initial 'street' is assumed in all of our models.

5 Generative spatial modellers

An urban spatial modeller, then, needs to represent not only urban structure but also the processes by which it is produced. (We use the term modeller here to refer to the computer algorithm which generates spatial arrangements, as it is used in CAD terminology, to refer to the technique used to construct models rather than the person doing the modelling). A variety of computational techniques now exist which link rule-based processes with the generation of complex geometrical forms. These techniques, including cellular automata, aggregation models and shape grammars, tend to rely on the repeated application of a number of simple transformations and on the computational power of modern computers. They have been developed in parallel with and informed by new insights in biology and evolutionary theory and into dynamic or chaotic phenomena in other fields (see Bunde and Havlin, 1994). The link with evolutionary biology has been noted by several researchers who have attempted to apply these techniques to the simulation of urban form (Batty & Xie, 1994; White & Engelen, 1993). However, models using generative techniques have tended to be applied at the larger aggregate scale and are aimed at finding general descriptions which are applicable to the entire urban system. In our approach, the intention is to examine the process at the scale of the unit of aggregation, rather than apply a generic model descriptively.

Procedures employing cellular automata (CA) are, by nature, useful in simulating area-based phenomenon. Cellular automata are essentially simple. They consist of arrays of cells where the state of each cell depends on the state of the neighbouring cells. Cells can be at any one of a number of discrete states. A definition of the cell's neighbourhood and a set of transition rules will determine the state of that cell as a function of the state of the cells within the neighbourhood. In each run of the model, all cells are updated simultaneously.

Apart from the Life Game, which was an early CA used to explore many fundamental issues of 'artificial life', they have been used to model a variety of dynamic spatial processes including the propagation of forest fires, epidemics and chemicals (Bunde and Havlin, op. cit. 1994). White and Engelen used CA to study the spatial distribution of various land use types, while Batty & Xie (1994) have studied the evolution of particular spatial configurations. Both these studies compared simulations to actual cities. One of the most successful, non-scientific, uses of CA as an urban modeller is the popular computer game SimCity 2000.

CA have several obvious limitations. The two-dimensional array on which CA are based is biased towards orthogonal spatial configurations. CA model regions well, but not linear structures. In urban situations the influences on development may operate at a variety of scales. Some researchers overcome this with a complex definition of a cell's neighbourhood involving distance functions for influences which are nearby, but not adjacent. This imposes a high computational overhead as the potential for development of each cell in the array is calculated at each iteration. This problem can be partly overcome by the introduction of global rules or the nesting of neighbourhoods at a variety of scales but the simplicity of the CA, which is one of its major virtues, begins to be forfeited.

Diffusion limited aggregation (DLA) essentially models a fixed object, usually represented in two dimensions, consisting of a collection of particles. The object is surrounded by a field in which sequences of free particles move at random. When a new particle strikes the object it attaches itself to it. Thus DLA describe growth, but not dynamic change as CA do. DLA models have been compared to fractal urban phenomena and are most useful for describing the transportation systems (Batty & Longley, 1994, p 247). Their dendritic structure is particularly applicable to hub based systems such as railways (ibid. p 243). The difficulty with DLA models is that the probability of new development is far greater at the periphery than closer to the origin due to the manner in which the model is generated and this limits its application to urban simulation. DLA tend to be dendritic and usually form non-distributed networks. Urban street networks, by contrast, most frequently take the form of distorted grids which are more highly distributed.

Shape grammars consist of a defined lexicon of spatial units each with a set of attributes, together with a series of rules for the combination or transformation of units. The permutations and combinations of such transformations quickly become vast in number. However, the possible arrangements can be limited to a series of templates for building types which have a consistent social meaning, where particular spatial arrangements are associated with cultural and social patterns of use. Within particular architectonic constraints, such forms tend to produce an identifiable 'architecture' which can, to some extent, be parameterised. For example, the spatial description of a church tends to be topologically similar, regardless of its size. Shape grammars tend to be more useful in the description of individual buildings rather than entire settlements. However, small settlements have been simulated using these techniques (see Herbert, Sanders and Mills, 1994).

Models developed using the techniques described here frequently exhibit fractal properties. The inventor of fractal geometry, Benoit Mandelbrot (1983), speculated that urban phenomena display many fractal properties and models have been used to simulate such measurable urban phenomena. Urban structures tend to have varying fractal dimensions. Batty and Longley have summarised several studies into this phenomenon (1994, p 242). They suggest that a typical fractal dimension for urban density patterns is in the order of D=1.7. The fractal dimension of urban infrastructures, including rail, bus and sewer networks tends to be closer to 1 (D=1.3 is the average of Batty and Longley's limited sample). These systems tend to have a more linear structure and the findings demonstrate the difficulties of using a single generative process in studying the interaction of several aspects of urban structure.

Different spatial modellers, then, appear to lend themselves to particular aspects of urban simulation - CA for land use patterns, density etc; mid-point displacement for terrain modelling and area/perimeter simulation; diffusion limited aggregation for service and transport structures; shape grammars for building typologies (Batty and Longley, op. cit. 1994). An integrated urban simulator needs to combine aspects of several spatial modelling techniques operating in a dynamic process and at a number of scales. The fact that the emergent form of the unplanned city is the result of a number of interrelated processes, in particular the distribution of activities, the development of the street network and the expansion of individual buildings, supports this approach.

6 Local aggregative models

The models that we have been experimenting with explore the manner in which the public network of the city and the associated distribution of activities develop. They employ techniques used in the 'beady ring' model described by Hillier and Hanson (1984, pp 57-61). This is a spatial model which simulated the growth of small, informally arranged villages and which was aimed at demonstrating how a fixed relationship between street space and built space resulted in a characteristic settlement form. This can be explained as a rule-based process determined by spatial and social constraints. It assumed three types of space: a closed cell representing an approximation of a house, an open cell representing a section of open street and a carrier space. House cells form a face-wise connection with street cells spaces to form a couplet. The rules of aggregation assume a new street/house couplet is added at each iteration providing there is space street space to do so, and that the new open space street space form a face-wise connection to an existing open space. Hillier and Hanson argue that this type of aggregative process can be used to illustrate the development of 'organic' settlement patterns they had observed in rural France, where buildings form irregular clusters and the open space is arranged in a series of irregular spaces connecting to form ring structures like 'beads on a string'. We will refer to this model henceforth as the 'beady ring' model.

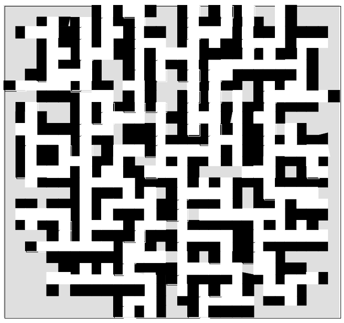
While the model demonstrated by Hillier and Hanson has been compared to cellular automata (White and Engelen, 1993, p 1177), in fact it combines aspects of several spatial fractal modelling techniques. It appears similar to a CA due to the two-dimensional array used in this case. However, while the cells may change state, the state change is one-off and irreversible and the model operates more like a shape grammar. In addition, the manner in which new spaces are aggregated to the extremities give it some qualities of an aggregation model.

In our work using the space syntax approach, we found it difficult to generate ring structures. The computer-generated beady ring surface illustrated by Hillier and Hanson (1984, p 219) demonstrates the problem (figure 1A). The street, house and carrier spaces can be examined separately. The emergent street network is continuous but not highly distributed. Rings do tend to form but so too do long dendritic structures, as in DLA models. Settlement patterns with a structure similar to this have been observed (Fonseca, 1976, p 103) but differ somewhat from the beady ring structure described by Hillier and Hanson, who acknowledge that a beady linear structure is consistent with the syntax model (1984 p 84).

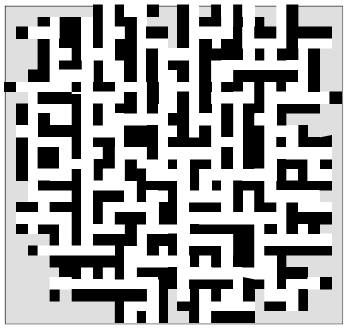
Analysis of the street network generated in this instance reveals that the total number of islands formed is 8 (figure 1). However, if one examines the distribution of house clusters, they number 52 (figure 1B). If house clusters are to be used as the basis for the description of rings, which would be consistent with Hillier and Hanson's argument and method of subsequent analysis, one needs to add to the street spaces a set of cells spaces which are not visited in the production of the model but which are surrounded by spaces that are. Figure 1B shows the extent of the network when vacant spaces surrounded by three or more occupied spaces are added to the network. This difficulty is in fact an attribute of the cellular nature of the model and would disappear if particular spaces could undergo topological transformations, which would allow them to stretch. The technique of generation therefore needs to be amended to introduce a method to include some or all of these intermediate spaces.

This problem is related to an issue of global feedback and its influence on the local generative process. As the model develops, certain opportunities arise where casual observation would suggest a connection between particular streets. In actual settlements this can be envisaged as the development of 'short cuts' and will only take place under certain conditions when a new street approaches an existing one. Larger knowledge of the network is necessary if such alterations are to be made. For instance, short-cuts will not be formed next to and parallel to one another. Short-cuts are most useful where they maximise the distribution of the network, making them an important component in the development of the settlement.

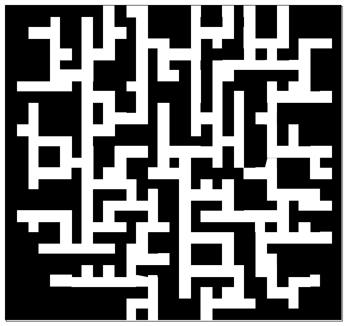
This leads to the question of precedence in the relationship between the formation of the street and activity structures. Do streets form as the result of movement patterns between destinations or do they form first allowing activities to locate on them? In 'planned development' the street pattern and the location of buildings, or more often the subdivisions on which they will be built, are laid down together, usually within the bounds of some larger division or estate. This has been common practice since ancient times. However in informal, 'unplanned' settlements there are several different ways in which the street pattern and the distribution of buildings can take place:



A. 'Beady Ring' surface (after Hillier and Hanson) with carrier space shown



B. The same surface showing houses and open space. Carrier space is included as part of the street network



C. The same surface showing street network actually created in the aggregation of the model. Houses and carrier shown black.

Figure 1. 'Beady Ring' surface (after Hillier and Hanson) generated by an accretive process to model urban form. At each iteration a pair consisting of a house (black) and a street space (white) was added over a carrier space (shown in grey).

-1 The street pattern and distribution of buildings develop concurrently, usually at a relatively low density. Blocks are established by the development of individual buildings into clusters which expand to fill available space (Saitas, 1990 p 42, Benevolo, 1990 p 981).

-2 The street pattern precedes the development of buildings and the land is subdivided. Houses develop on the edge of roads and plots are developed behind them over time. Plots are defined in terms of a unit length of street frontage (Buttner & Meissner, 1983, p 46). As the movement economy develops particular streets will have a favoured place in it and building on these streets may develop according to the higher value associated with their location.

-3 Buildings are constructed prior to any street network. Rough foot tracks form, often parallel, connecting houses to local services such as water points, transport, or shopping facilities. The location of such attractors therefore becomes important in the formation of the street pattern. As the settlement consolidates, the more dominant of these paths develop into streets. Plots expand to fill the available space (Fatouros & Chadjimichalis, 1979; Schaur 1992, p 22).

The Hillier model proceeds by the addition of street/house pairs. While this is consistent with their syntactic description, it is not required by it, nor is the condition that one and only one house face each street space. In the development of actual settlements the system of streets and buildings are not so rigorously connected. Houses develop on existing streets, as well as on new ones. This suggests that a model where the development of streets and buildings (land use activities), in this case houses, is less constrained but develops as a result of two interrelated processes. To be useful in studying informal settlements these need to be modelled at the basic unit of accretion, that is at the scale of the house or smallest land division.

7 Settlement aggregation experiments

Our work has involved the development of a series of spatial modellers with the following aims: to avoid the rigidity of a two dimensional array, to model urban street patterns with an accretive process, to model the process of building type development and to introduce the dynamic process associated with shifts in the movement economy. We have developed several prototype modellers each with a different emphasis but all broadly based on observed built-form to illustrate how the development of movement systems and building typologies can be combined in a single model.

As we have suggested above, urban form is characterised by a variety of plan areas each with distinctive characteristics and resulting from particular practices. These may develop simultaneously and at a range of scales. They may include, for example, the clustering of development along existing lines of movement, the subdivision of estates, accretive additions on the urban fringe or the restructuring of buildings and uses as a result of changes in the movement economy. Our initial aim is to develop a series of related models which demonstrate these differing aspects of urban morphogeneisis. A longer term goal would be to combine them in a larger and more complex model. While the emphasis to date has been on the local-to-global influence of local processes we recognise the importance of global-to-local pressures on these, which need to be examined at the larger scale and would manifest and influence primarily through the movement economy.

The three models described below are essentially similar but are used to explore different aspects of urban morphogenesis . All are based on the original 'beady ring' model. However, they include more complex rules for limiting the manner of accretion and more detailed descriptions of building types. At present the primary means of verifying the models is through casual observation. The comparison of figures 2 and 3 suggests that the method may have some application in planning practice.

Like the 'beady ring' model all our models consist of an algorithm which produces a spatial arrangement of closed and open cells, which represent buildings and streets. The basic operation of all the models is governed by a process which selects an existing open cell (street space) at random and attempts to place a new cell (or group of cells) adjacent to it. A key difference is that, rather than adding a fixed arrangement of open and closed cells at each generation, such as the couplet in the 'beady ring' model, our models add closed and open cells in an alternating sequence models the alternating accreation of closed and open cells. This allows differing rules to govern the development of the street network and the development of building types.

While the manner in which information is passed through the models is similar, however the exact nature of the information differs in each model. Conceptually, information is stored in three ways. Firstly, there are sets of global attributes of the

Figure 2. Jhuggi Area in Delhi. Example of simple house type aggregated in a manner typical of informal settlements. Houses form clusters as well as along streets (from Steinerg and Raj, 1990).

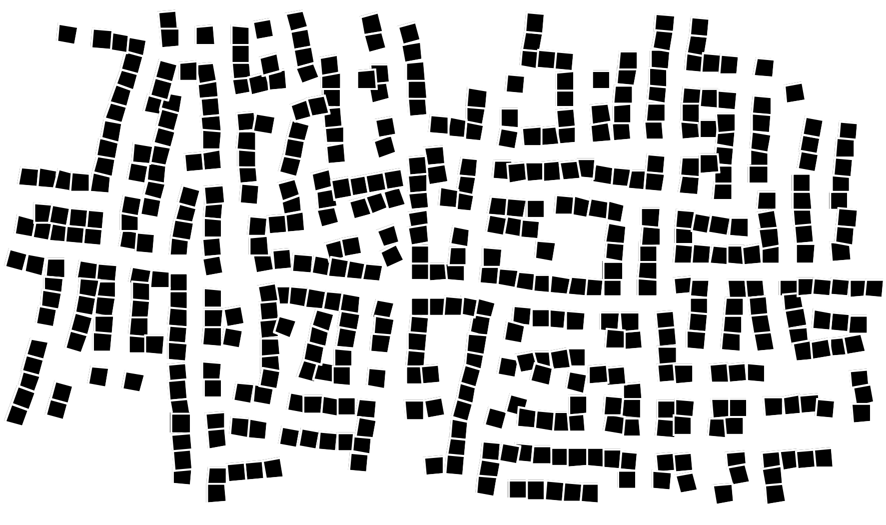


Figure 3. Computer generated model of settlement pattern. Model developed from 'Beady Ring' syntax.

model, in particular the total number of various cells and a set of parameters used in evaluation of generative rules. Secondly, information is stored spatially. As the model develops, 'tests' are carried out to retrieve information about other spaces in the neighbourhood of a parent cell. This type of test is used for the most basic rule: that a new cell cannot occupy the same space as an existing cell. Thirdly, each cell carries its own set of attributes, such as its name and type. Because new cells always join to existing cells, information can be passed from parent to daughter, for example information about orientation. This can provide cells with a certain amount of information about their place in the movement network, for example the distance from the initial seed cell. This type of information is carried by street cells only, as all new street cells and house cells have a street cell as a parent and can be used to determine their state. The accretive process also enables cells to be grouped into more complex objects. Street cells can be grouped to form streets (that is linear entities) and closed cells in complex arrangements to form larger buildings conforming to particular typologies. Because of the accretive nature of the model, entities such as streets can have a variety of attributes which can be passed to daughter spaces. This saves the need to recalculate the global state of the model at each iteration, as with a CA.

The models are created as macros of the CAD program MiniCad+ and are written in MiniPascal. They are created as two dimensional CAD models with each cell having its own data record. Building heights are given as an attribute of the cells and are used to create three dimensional views of each aggregation on completion.

8 Path node generator model

Figure 4 shows a typical sequence in the development of this model. The model consists of five types of space;

- a carrier space
- two types of specific open space - street cells and road cells
- two types of occupied space - house cells and garden cells

Street cells are represented by a white square and have an orientation. A road cell is like a street cell except it is not a site for aggregation and is used only in the initial set-up to represent an existing movement structure. Houses are represented by a black square. Gardens are represented by a hatched square and are also square. Gardens have face-wise connection with the rear of a house. The house and garden form a couplet whose orientation is determined by that of the parent street which they face. This couplet forms a basic building type, which can be thought of as a unit in terms of the development of the network and the syntactic description.

The initial set-up consists of a linear arrangement of road cells and a number of 'seed' street cells placed along it in groups to form small squares. This arrangement is somewhat arbitrary but could represent a peripheral urban road with a series of nodal points which may contain a fixed public resource such as a well, a bus stop or other amenity, which are shown in the figure as a small circle. The number of these initial nodes is pre-determined as part of the set-up and is generated parametrically as part of the model: in figure 5, it is 3 and in Figure 6, it is 2. In other respects these examples are the same.

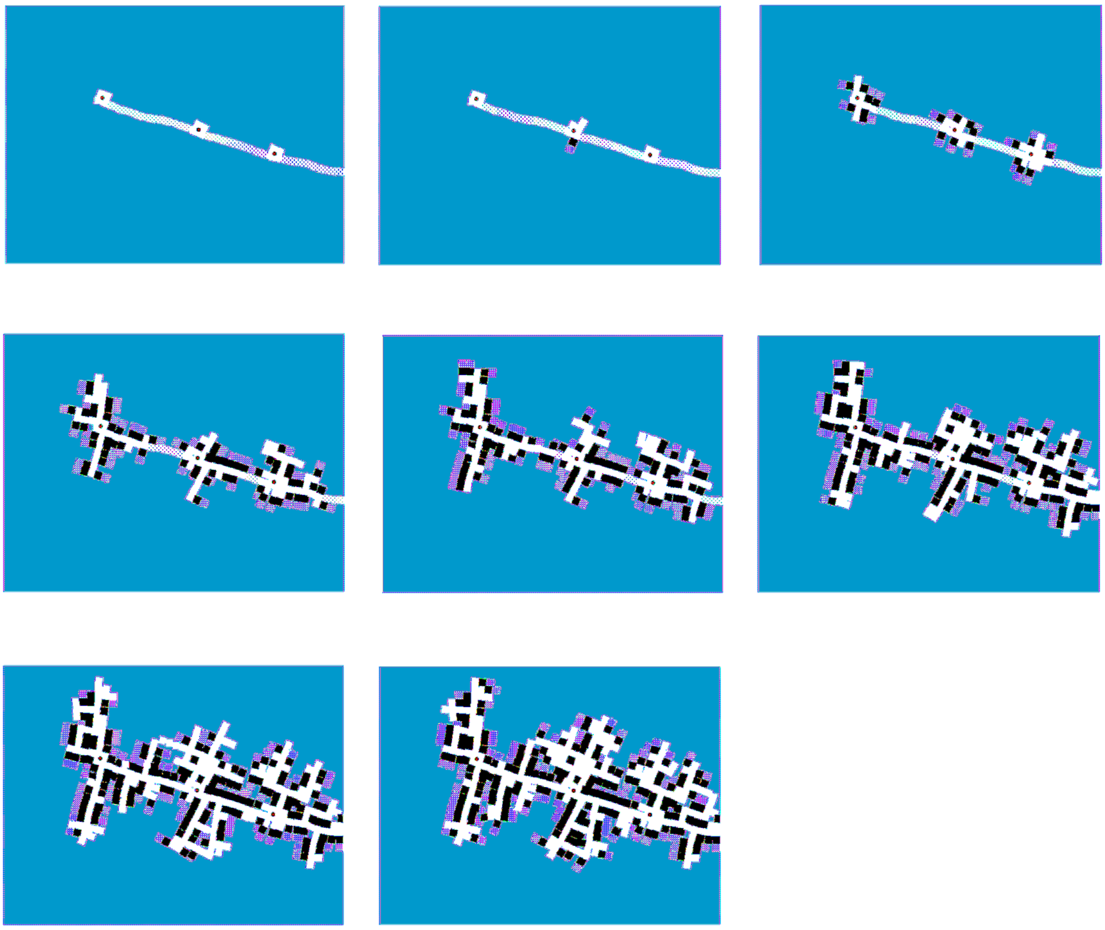


Figure 4. Sample output of settlement simulation model, Path Node Generator. The model operates by the addition of street spaces (shown in white) and buildings (shown in black). Each building has an associated garden space shown in light grey. The model, in this instance, assumes an initial street and three small squares.

The basic rules for aggregation are as follows.

Street cells and house cells are added alternately to parent street cells selected at random, providing a localised spatial test reveals space is available (see figure 7A). If the neighbourhood test reveals the space is part of the carrier, then a new cell is added at that site. A new cell has a face-wise connection with its parent street cell. Where there is space behind a new house cell, a garden cell is added to the house to form a couplet. In some instances an existing cell can be replaced by a new cell. A street cell will replace a road cell and adopt its heading while a house cell will occupy the space of an existing garden but not adopt its heading.

The development of the model is constrained by several other rules acting at a local level. The model selects the orientation of new cells randomly, but within a pre-set probability distribution. In the instances illustrated in figures 4, 5 and 6 a new street cell is likely to adopt the orientation of its parent but may have an orientation of ±90°. Each cell has a heading and a spatial test is carried out at heading +90°, heading -90° or heading +0° to establish the state of the space in that area (Figure 7A). The direction of the test is determined probabilistically and varies depending on the nature of the cell being added. When placing a new street cell at +90°:-90°:0° it is 10%:10%:80%. The exact heading of a new street cell is varied by between ±0-5° to introduce some irregularity. The location of house cells is similarly constrained and the probability of placing a new house cell at +90°:-90°:0° is 50%:50%:0%. These rules in combination give rise to an irregular grid forming a loose orthogonal pattern which can be observed in many actual informal settlements.

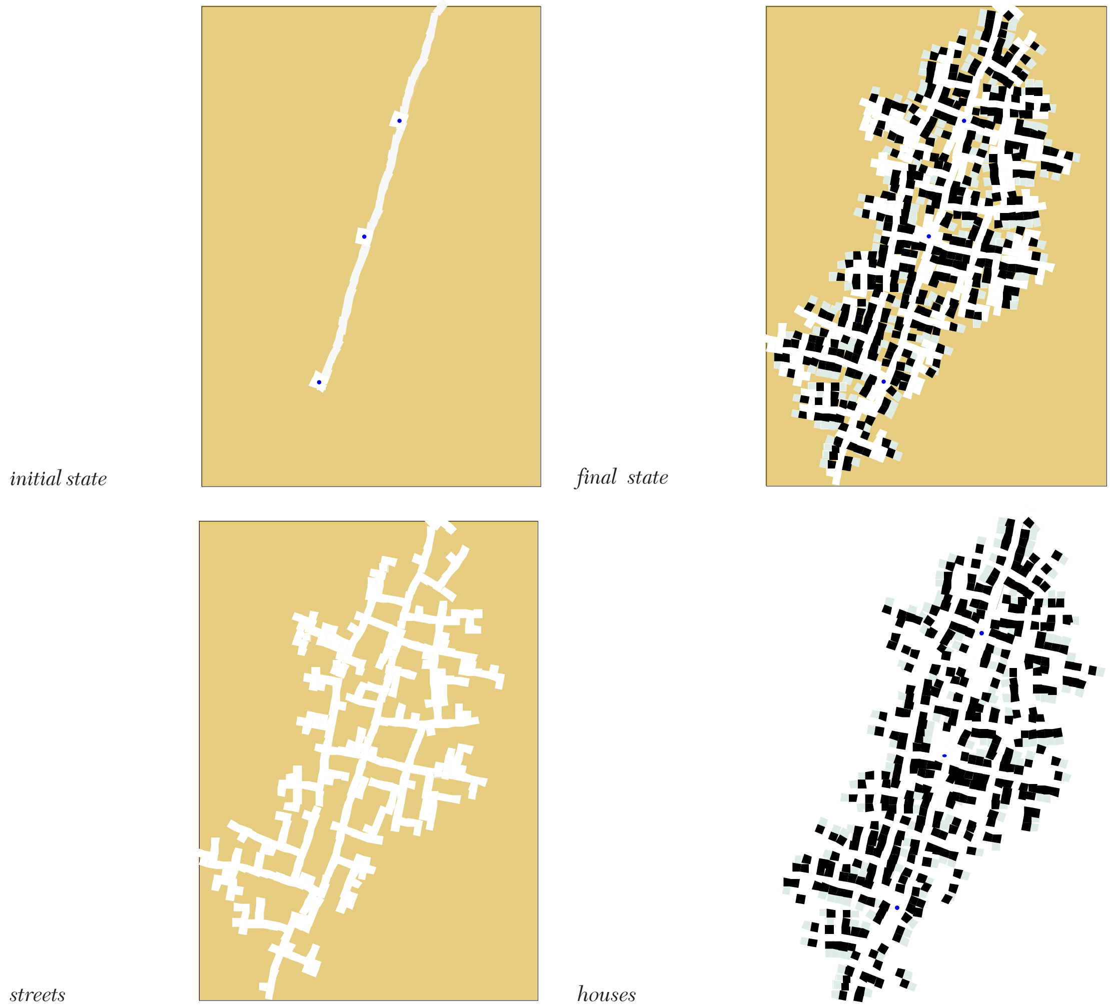


Figure 5. Sample output of settlement simulation model, Path Node Generator. The initial and final states of the aggregative process. The street layout and houses (with associated gardens) are also shown separately. House cells are shown black, streets white and gardens in tone.

The rate at which houses are added can be varied as part of the set-up. This variation will have an effect not only on density but also on the emergent street pattern. Consider the two instances in figure 8. These have an identical initial set-up with the exception of the house rate which is set at 1 and 2 respectively. The higher house rate reduces the number of possible parent sites for new street cells and produces a more linear and less distributed street pattern.[1]

Unlike the 'beady ring' model the path node generator model includes additional rules aimed at producing a more integrated street network. A simple mechanism is used to constrain the spatial arrangement of the settlement. The model is used to explore the manner in which a settlement might spread out from fixed infrastructure. As the settlement expands, each new street cell records the number of steps it is distant from an initial square. A street cell is only available as the parent site for a new cell if it is within a certain distance from the origin. As the model grows, the maximum distance is increased.[2] This mechanism creates a type of gravity effect in relation to the initial squares.

This model also addresses the issue of the 'short cut' discussed above by introducing a more complex spatial test for new street cells. As each new street cell is placed, the program tests the neighbourhood for other streets and, if found, places an additional street cell so as to join them (see figure 7). Although this is only a very local test, we

Figure 6. Sample output of settlement simulation model, Path Node Generator. The initial and final states of the aggregative process. The street layout and houses (with associated gardens) are also shown separately. House cells are shown black, streets white and gardens in tone.

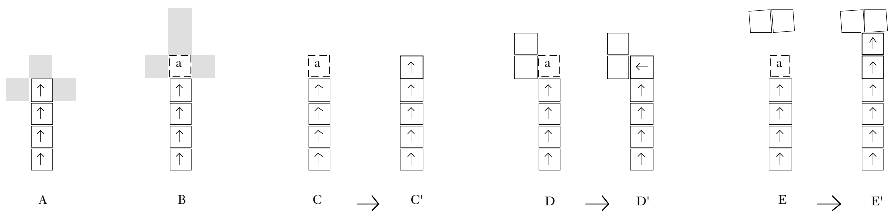


Figure 7. Test mechanism. Existing street cells are represented by squares, arrows show their heading. A: The normal spatial test checks the state of the space adjacent to the parent cell. The shaded area is the defined neighbourhood. The test is carried out on one heading selected at random but repeated several times. B: Additional test to check for existing street cells in the neighbourhood shown shaded. The test is carried out firstly in front and then to either side in one operation. If no other street cell is encountered, the new cell is added as in instance C, C'. If a street cell is encountered in front, then additional cells are added to join to it as in example D, D'. If cells are encounted to either side, the heading of the new cell is altered as in instance E, E'. This prevents streets forming in parallel rows.

found that this addition to the model produces a very much more distributed network. In addition the model could be adapted to include a measure of the total street network, such as its average connectivity or relative asymmetry, and this type of global feedback could be used in altering the rules for aggregation.

9 Street and building use model

This model operates in a manner similar to the previous one but has been used to explore other aspects of urban form and differs in several key ways. In this model the

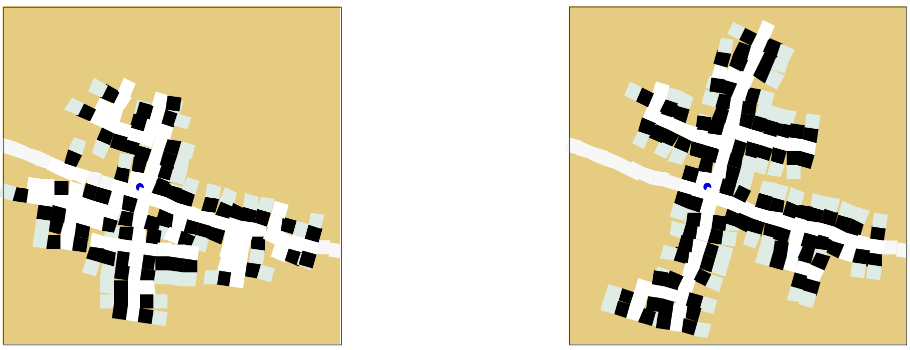


Figure 8. Sample output of Path Node Generator where house rate, in instance A, is set at one per street cell while, in instance B, it is set at 2 per street cell.

street network develops in advance of the distribution of land use activities and street cells are aggregated into linear groups. The archetype for this model is the English village. While the basic set up is similar to the above model, the description is more complex. Figures 9, 10 and 11 show typical output of the model.

Buildings in urban environments change over time. They are extended, vacated and reused or replaced by other buildings and these changes will affect either the form of the settlement or the movement economy. Apart from the construction of new buildings, a major influence on the emergent form of the town is the extension of existing ones. Buildings may also change in use rather than form. One of the dominant influences on the location of particular uses is their location within the movement system. Particular use types such as commercial and retail uses will accumulate along the more spatially-connected streets. Developments are translated into property values which are a function of the size of the site and its relative location in the street system, as well as of the character of the buildings on that site. When the value of a site is worth more as another use, the building is generally converted or replaced sooner or later. This model introduces a simplified model of this change in building form and use.

The model consists of four types of space:
- A carrier space
- Two types of specific open space - street cell and road cell. Street cells may be 1 of 5 classes and do not change class.
- One type of occupied space representing a house cell. House cells may be in one of 5 states representing various building types.

Street cells are arranged in groups to form streets or squares. Streets are formed as linear entities consisting of a series of discrete street cells which are positioned in consecutive iterations of the model and have common attributes. At each call for a new street cell the program will perform one of two operations. Either it will select the most recent street cell as a new parent cell, adopting its heading and extending the street group, or it will select another cell at random and commence a new street group on a new random heading. The probability of this choice is determined as part of the set-up and will vary with the class of street.

The length, location and orientation of the initial street are determined as part of the set-up. It is intended to represent a pre-existing artefact which will form the nucleus of the new settlement and forms a seed for development. New streets will develop in a particular manner depending on their location within the developing network. A street's probable length is determined as a function of its connectivity to the initial seed street. The less well connected streets will tend to be shorter.

There are five classes of street groups. The initial street is class 1. The class of streets is determined by the class of the parent cell at their origin. A class 2 street will have a cell of class 1 as its origin, a class 3 street will have a cell of class 2 as its origin while a class 4 street will be generated from a cell of class 3 or 4. In the example shown, the probability that the existing street group will be extended rather than a new group started is 92%, 85% and 75% for streets of class 2, 3 and 4. The fifth class is that of a square which is an array of street cells, 2 to 4 cells in each direction.

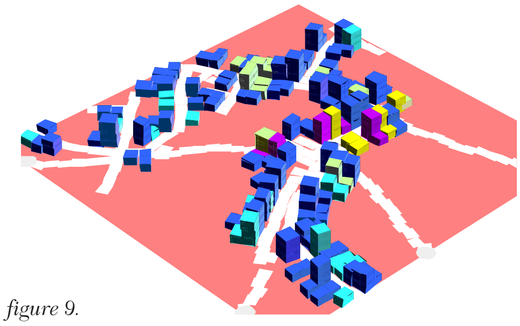


figure 9.

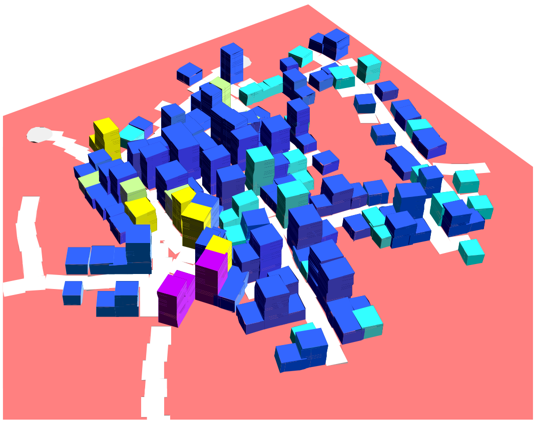


Figure 10.

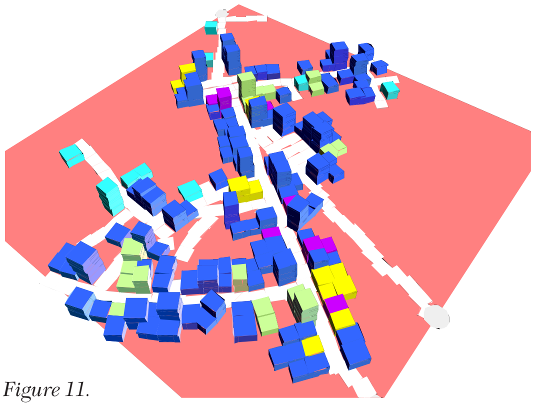


Figure 11.

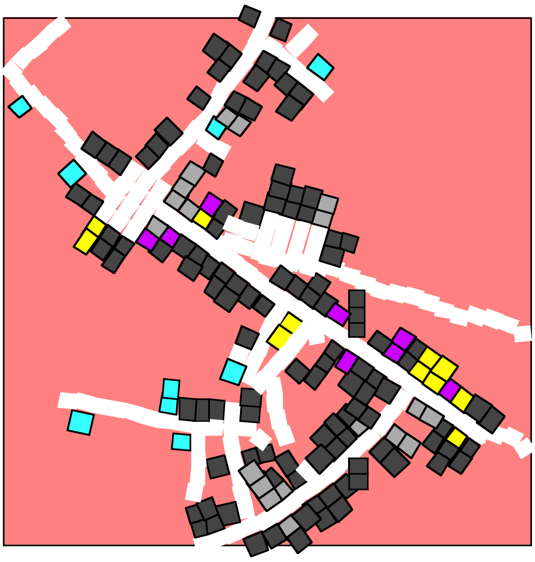


Figure 9. Sample output of settlement simulation model, Street and Building Use Generator. The streets, shown in white, are produced as sets forming linear entities. This model includes five building types shown in differing shades of grey. Demand for each building type is determined as a function of the total number of buildings and as a function of the location within the street network.

Figure 10. Sample output of settlement simulation model, Street and Building Use Generator. The streets, shown in white, are produced as sets forming linear entities. This model includes five building types shown in differing shades of grey. Demand for each building type is determined as a function of the total number of buildings and as a function of the location within the street network.

Figure 11. Sample output of settlement simulation model, Street And Building Use Generator. The streets, shown in white, are produced as sets forming linear entities. This model includes five building types shown in differing shades of grey. Demand for each building type is determined as a function of the total number of buildings and as a function of the location within the street network.

In addition to class and heading, street cells have attributes which are determined by their relative location in the network including 'value' and 'node'. In this model, value is a loose index of property values of sites facing that street and is determined in a simple manner. It is a function of the cell's class, being highest for class 1 and lowest for class 4. Nodes are formed at the junction between street groups. The parent cell at the origin of a new street will have the attribute of node. Additionally, when a street group encounters an existing street cell, the group will not be further extended and the encountered cell is given the attribute of node. Finally, if a cell is a node, becomes a node or is adjacent to a node, it's value is increased by 60%. This reflects the privileged position a node has in the movement economy.

The initial set-up consists of the initial street and several roads which adjoin it, but no house cells. Roads are similar to streets and represent pre-existing artefacts. They can be thought of country roads communicating to other external locations. They are determined parametrically as part of the initial set-up. In the instances illustrated in figures 9 to 11, there are three such roads. Buildings will not form on roads. However, if a test for a potential street cell street encounters a road it will adopt its location and orientation. In this manner a road space can be converted into a street space and become part of the accretive process. The aggregation model commences by the addition of a class 2 street to the initial street.

Following the addition of each new street cell, a procedure to add a number of house cells is called. This number can vary. In the examples in figures 9 to 11, it is set at 6. Rather than simply adding a new house cell, if space is available this call will do one of three things. Firstly, it will add a new house cell where space is available. This new cell may be in one of 5 states. Secondly, if the test encounters an existing house cell, rather than adding a new cell elsewhere it will extend this existing one. This is done either by adding an additional cell behind it, or if there is no space, by adding an extra storey to it. Thirdly, it may change the state of the cell from one building type to another.

The state of a house cell is determined by two factors. State represents building type, which is associated with function. The five types in this model are arbitrary but let us assume the following simple taxonomy of village buildings; 1: a normal dwelling; 2: a dwelling/workshop; 3: a commercial premises, 4: a building housing a social institution, and 5: a second type of dwelling of lower cost and status. The potential mix of these buildings can be given as a percentage of the total or as a ratio of the base unit, in this case the type 1. The model will normally add the type 1 cell, but after n number of cells have been added demand will be created to add one of another type. For the instance illustrated n is 15, 25, 30 & 2 for types 2, 3, 4 & 5 respectively.

In actual settlements some building types will be attracted to well-integrated locations, those of higher value, while others are attracted to sites of lower value. In the model, each building type has a threshold value which limits the range of potential parent street cells. When a street cell has been selected as a site for aggregation its value is evaluated. Then for each building type in turn, commencing with that with the highest value, the procedure determines, firstly, if there exists demand for that building type and, secondly, if the value of the particular street cell exceeds the threshold for that building type. If so, then the new cell is of that type. If not, the same procedure is carried out for a building type with a lower value threshold. If no other building type is called for, the new cell will be of type 1. For the instance illustrated the threshold values are >30, >60, >75 & < 30 for types 2, 3, 4 & 5, respectively. If, in the call, the spatial test encounters an existing building a similar procedure is used to alter the state of the existing house cell, if demand and value permit.

10 Subdivision generator

This model is more constrained. It operates in a manner similar to those described above. In this case, the development of the street pattern is more regulated but more complex rules apply to the development of individual houses. It was developed to illustrate how individual building complexes might develop and the influence they may have on subsequent urban form. It is, in essence, a shape grammar and assumes a more ordered development of streets, as might be typical of an illegal subdivision for residential use which is commonplace in much of the developing world.

The description of houses is more complex than in the models described above. It assumes a process whereby an individual plot is acquired and then houses are built and expanded over time by their occupants. Initially, a simple dwelling is constructed,

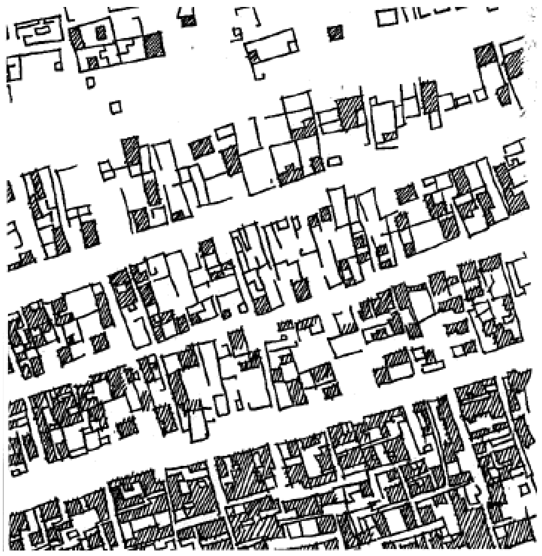


Figure 12. Typical progressive development of density and plot coverage in North Africa (after Davidson & Payne, 1983) used as an example for the subdivision generator.

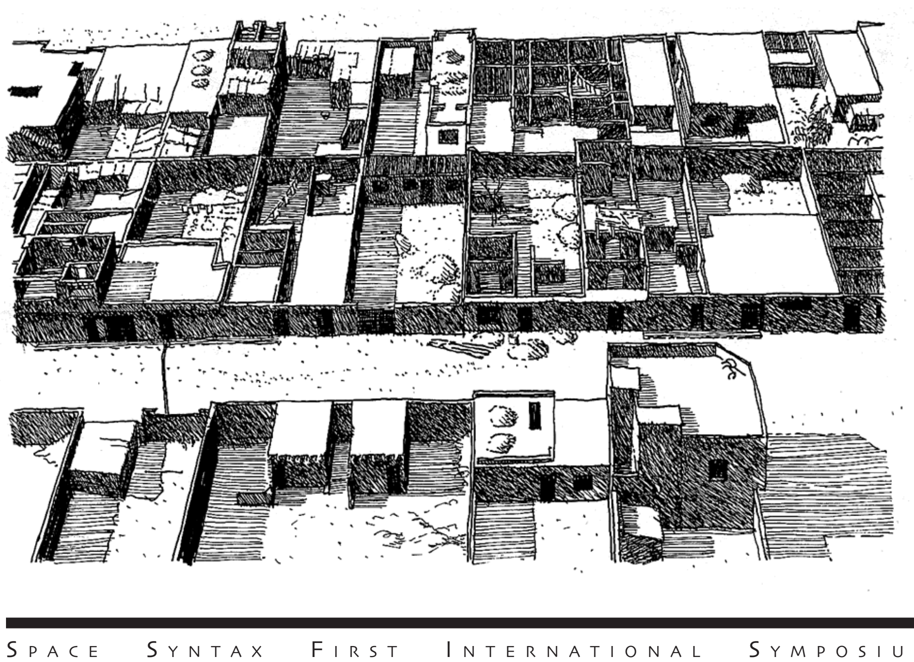


Figure 13. Stages in the progressive development of a 'barriada' in South America (after Mangin & Turner), used as an example for the subdivision generator. This example demonstrates the manner in which varying levels of investment by different owners creates an uneven pattern of development.

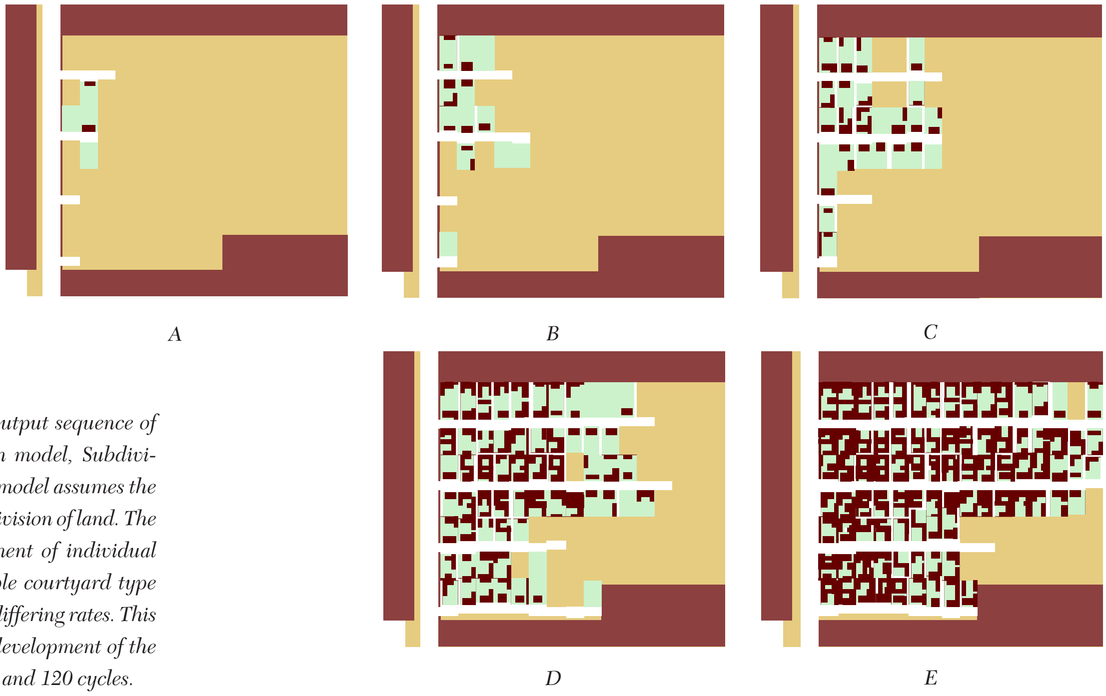


Figure 14. Sample output sequence of settlement simulation model, Subdivision Generator. This model assumes the semi-structured subdivision of land. The subsequent development of individual plots assumes a simple courtyard type built in stages and at differing rates. This sequence shows the development of the model at 3,10, 24, 60 and 120 cycles.

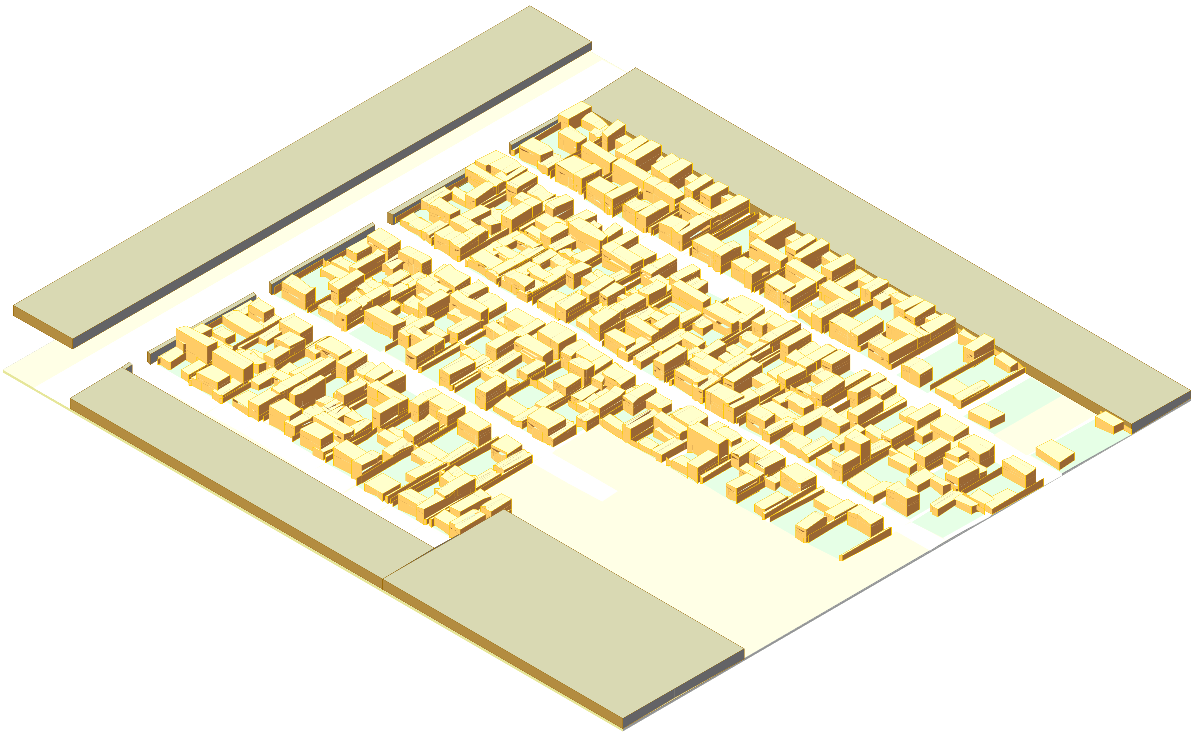
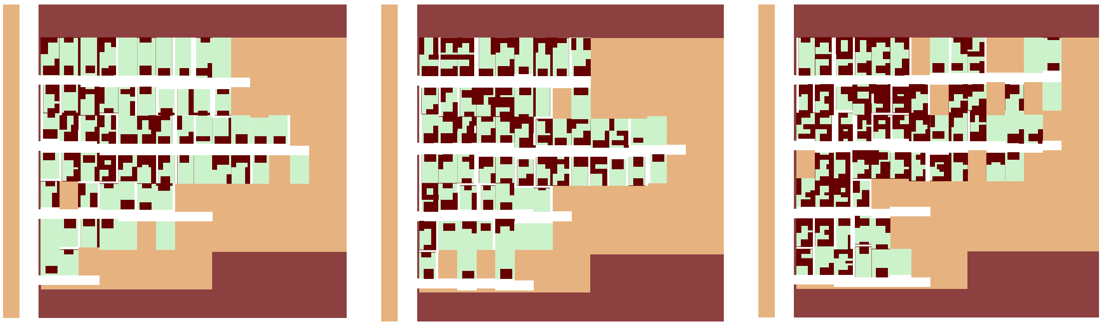


Figure 15. Sample output of settlement simulation model, Subdivision Generator. 3D view of model in figure 10.

perhaps consisting of a single room which is expanded by the addition of other rooms. The model assumes only one type of building. In this example the land is assumed to be divided into approximately equal plots. While in this study the rules which govern the formation of house types are rather simplistic, culturally-specific rules can be derived from the study of existing settlements and applied as a shape grammar model (see, for example, Herbert, Sanders and Mills, 1994). Figures 12 and 13 exhibit the type of development typical of that assumed in the model.

As with other models, the program first adds a street cell. In this case the heading of a street is always the same as the parent cell. The location of street groups is determined parametrically. The model then makes a number of attempts to locate a new



A B C

plot adjacent to a street cell selected at random. If a plot exists, it 'builds' a house on the plot. If a house exists it extends it. The first room on the plot is located at the front. A typical sequence is illustrated in figures 14 and 15. Once a plot has acquired a certain number of 1-storey rooms (in this case set at 5) upper floors are added as attributes of each room.

The basic elements of the building typology consist of:
- The plot, the size of which is determined by the street pattern.
- Seven locations for 'rooms', the exact sizes of which are randomised within parameterised limits; rooms may have a number of storeys.
- Perimeter walls
- Side pathway
- Rear pathway

While the arrangement of each building is random, the probability of certain features is determined as global attributes of the model's set-up including the possibility of a side or rear pathway on any particular plot, the maximum number of storeys and the range of the size of rooms, which is variable within given limits. Other global attributes are set as part of the set-up, in particular the rate at which buildings develop in relation to the addition of new street cells, which will influence the average density of development (see Figure 16).

As with the other models, this one involves a spatial test to determine attributes of the neighbourhood. However, in this case, attributes of neighbouring house cells will influence the manner in which plots develop. A proportion of plots (in this instance, approximately 1 in 6) will develop a separate building at the rear of the site. This may be typical of a plot occupied by two households. In such cases a side lane is always added. When a new plot adjoins an existing plot with a side passage this is revealed in the local test and the new plot develops a side and rear pathway which links adjacent streets (see figure 17). New plots with pathways will always develop side walls.

As the settlement develops, older plots tend to become increasingly built-up. They may also develop upper floors as the ground becomes increasingly covered over. This process typically results in a type of courtyard housing emerging as the final form, but with a variety of intermediate forms which are influenced by the form of neighbouring plots.

Figure 16. Sample output of settlement simulation model, Subdivision Generator plot development. This illustration shows the manner in which local influences will affect the subsequent built form. Two examples are shown demonstrating the influence of a side lane on an adjoining plot. The development of each plot is randomised and mostly autonomous, but is subject to some local influences of neighbouring plots. The sequence A, above, shows a typical development of two adjacent plots. The sequence B demonstrates how the development of a new plot (shown empty) will differ where the spatial test of neighbours reveals it joins at its rear to an existing plot with a pathway. A plot with a rear pathway may develop its initial building at the rear rather than the front of the plot.

11.24

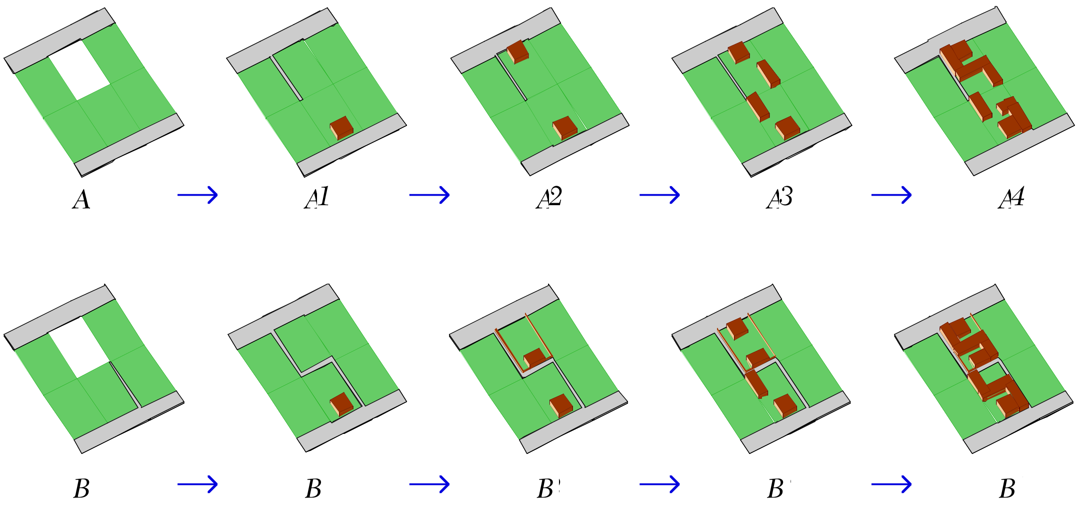


Figure 17. Sample output of settlement simulation model, Subdivision model. Within the model the probability of particular attributes can be adjusted including the probability of a side lane forming, the maximum height and the density. These examples show the variation in emergent form as a consequence of variations in these global parameters. The density is governed by a density factor which relates the rate at which existing buildings are extended to the development of new plots, that is the number of attempts to locate or extend a house for each new street space attempted. In these instances this factor is increased from 1 in A, to 2 in B, and 4 in C.

11 Application of the models

These three models illustrate varying aspects of urban development. The first shows the relationship between built form, access and infrastructure, the second examines the manner in which buildings may change as a consequence of the overall development of the settlement and the third demonstrates how socio-spatial codes might be modelled. More complex models could combine all three, as well as including other factors not discussed here.

In urban development there is always a trade off between centralised planning exercised for or in the name of the public interest, with the aim of maximising the effectiveness of the urban system as a whole, and the rights and needs of individuals, firms or households acting to maximise the utility and amenity of a particular site. These two processes may be in conflict. The need is to exert the minimum control to the maximum effect by encouraging rather than enforcing a particular form of development which will suit the lifestyle of the local inhabitants. Generative models can be used to determine which factors are critical and can be regulated to give the desired objectives.

The tools we are developing offer planners the opportunity to explore the impacts on the physical urban environment of different levels of intervention in the urban development process. The purpose of the models developed thus far is to establish typical patterns of development within the context of rapid urbanisation in developing countries. By predicting likely settlement characteristics, this type of modelling can help inform policy towards informal settlements and their future upgrading and gauge the effect of strategic interventions, particularly formal decisions about transport and other infrastructure. The purpose of such modelling is not to predict the exact location of a particular building or space but to establish typical patterns of development. In order to do this, a large number of 'near fit' examples need to be produced and compared so that their common trends and tendencies may become evident.

The models have been developed as macros within commercial CAD software enabling visualisation of the urban settlement pattern and housing form. The parameters of each of the models are easy to adjust and the effects of the on-going development process can be readily understood. The idea is to develop an interactive tool which will facilitate the widest possible participation of residents in the planning process.

Generative models of this type offer considerable potential. When developed into more complex simulators, they could be used to produce varying scenarios for development and urban change. They could be used to assess the effect of new building codes or impact of major planned interventions in urban systems, such as the construction of new infrastructures. They might be used to explore the likely impact of changes in the development process itself brought about by cultural or technological change. As well as modelling impacts on existing development, they could be used to suggest completely new forms of development. They might also be used to provide synthetic data for aggregate land use transport models at the macro scale.

While at a relatively early stage in their development as planning tools, the aggregative models that we have produced thus far have opened up many avenues for exploring urban development, and for creating links with other theoretical approaches to the understanding of the development of urban form as a dynamic process.

Acknowledgements.
Much of the early development of these models was carried out by Bill Erickson while at the University of East London with the help and support of Paul Coates.

Notes

1. As the model grows the number of potential sites decreases as a proportion of the number of possible parent cells. The proportion of new street cells to new house cells is set as a parameter of the initial setup but is open to some small variation. To reduce the computational overhead on the model some functions are timed out after a number of attempts, such as the number of attempts to place a house after a street has been placed. In the instance shown, this is limited to 18. This will, on some occasions, cause two street spaces to be placed consecutively.

2. The potential size of the arrangement is incremented in a series of cycles. Where S is the maximum number of steps permitted from the origin and P is number of iterations (attempts) in the cycle. S and P are incremented to S' and P' at the end of each cycle.

$$S' = S+2 \text{ and } P' = P(3)$$

In the example shown $P = 200$ and $3<S<19$. This function is derived by casual observation only and is based on a crude measure of the size of the arrangement. Further, the measure of distance does not measure the most direct route to the origin. However it demonstrates the manner in which such functions can be introduced and is effective within the aims of the model.

3. The intention is that more intergrated streets would have a higher value. It is assumed that the initial street and the class 2 streets, which are probably the longest, will be the most integrated. This is not always the case, but as yet these models do not include a dynamic measure of the network integration. In the example given, the values attributed to streets class 1, 2, 3, &4 are 80,40,20&15.

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