The Use of CAAD to Generate Urban Form

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The paper describes a computer modelling process suitable for the generation of townscape elements using a statistical simulation based on aesthetic theory in mathematics. This approach is also used to analyse existing urban settings and thereby allow comparison with the generated output of the model indicating close agreement between the model and attractive historical townscape. This agreement depends closely upon the size of the unit chosen for measurement of *the existing townscape thereby determining how the output from the model should be scaled for construction. An independent low-level designing ability appears inherent in the model and there is a discussion as to how this might be further developed.*

Keywords: emergent form, generative model, power laws, townscape, vernacular style

1 Introduction

This paper describes a modelling system for the of townscape in the context of urban form. Previous studies on the generation of urban form fall into two broad categories. One treats the creation of a settlement pattern as an application of generally abstract, usually mathematical, principles at the macroscopic scale. The other applies generative principles whereby individual forms or elements of the urban structure relate to each other in space.

A good example of the first type is provided by Batty, Fotheringham and Longley [3] where diffusion limited aggregation has been used to generate the entire settlement structure. The general success of this class of model is judged by its resemblence at various scales to actual settlement patterns. Measures of fractal dimension are used in this instance to determine the degree of resemblence.

The other type of urban model is typified by the work both of Hillier & Hanson [13] and of Brown & Johnson [6]. The latter used generative rules derived from inspection of old city records to simulate the development of plots of land in London in the later Middle Ages. These rules were then modified as required to allow the model to generate form approximate to that actually found on site. Hillier & Hanson used a somewhat less specific set of rules but apply them more generally to produce the entire settlement form.

An interesting aspect of these last two approaches from our point of view is the introduction of a historical perspective, of the specific recognition of time in the modelling process. Also both seek to apply rules concerning the relationships between individual architecturally conceived elements of the urban structure. In this sense they are related to, but differ from the generation of architectural forms through the application of shape grammars [21,25].

2 The development of historic towns

A search through the literature indicates an inverse link between the detail embodied in the rules employed at the level of the individual building and the ability to simulate urban form at the large scale.

We suggest that while a single set of generative rules is sufficient to produce complex and unexpected patterns and behaviour, a more complex model with different though possibly related rules operating at different, higher, levels of complexity may be required. Through the novel application of an established statistical technique we hope to demonstrate a connection between the attractiveness of buildings in the townscape and the historical process of urban growth and structure. We use the word hope because this attractiveness like other things will be in the eye of the beholder.

Brown and Johnson point out in their study that the rules and principles used in the construction and location of buildings were largely implicit rather than explicit. Indeed many structures in historic towns where land had become scarce were created with the express-intention of avoiding compliance with laws and building regulations. It is difficult under these conditions of emerging form to state and empirically test hypotheses concerning morphogenesis. In our model we seek to avoid this problem by adopting a technique for the creation of form which recognises the practical limitations inherent within a site without employing precise deterministic rules for generation. The aim is both to create individual structural forms, although simplified, and through the same approach combine them to produce townscape and give an indication of urban structure.

There are two basic principles of structural growth identified by Brown and Johnson in the case of London and which plausibly would apply to other settlements. They are:

(1) buildings are constructed against existing property boundaries, and

(2) buildings formed continuous rows.

As stated above these can be seen as implicit rules, a reaction to the prevailing economic conditions and land ownership, rather than the result of direction through regulation. Although such regulations certainly existed they were most often introduced in order to deal directly with social conditions of health and disorder rather than specifically to determine built form. Specific regulations regarding building structure and design followed later in the C19 in the United Kingdom.

Apart from these simple principles of structural growth the built form we see today is also the result of demolition, redevelopment and the division and merging of sites. Where patterns of individual ownership of sites exist this generally takes place slowly and independently over time although there will be bursts of coordinated activity. Large scale demolition of private property and redevelopment as in the slum clearances of the 1960s and 1970s is comparatively rare. Through almost 2000 years of what now seem like haphazard changes the City of London has developed from a Roman settlement and the form of the modern city still reflects its origins. The main thoroughfares of Cheapside and Cannon Street in the old City still follow Roman alignments even though the buildings which line them meet the modem functions of international finance.

This haphazard appearance raises important issues. One is the extent to which what we see really is random. Given that we have thrown a protective net of conservation legislation over whole areas and not just over individual buildings we appreciate what we see and experience there. The visual attractiveness of the townscape consisting in the main in the disposition of buildings in space is something that both the average tourist and the professional architect acting as conservation officer are able to agree upon even when many of the individual buildings are themselves unremarkable. We are entitled to ask whether a purely random sequence of independent events is capable of producing this quality of attractiveness when we might more logically expect to see disorder and also to ask if this attractiveness has anything in common with the formalised standards of beauty implicit in recognised architectural styles. It would help if we could know the extent to which an event having occured in haphazard manner then predetermines following developments. If our cities have evolved, was this evolution a purposeful process and one with natural selection at work?

There is a strong analogy with the organic underlying much analysis of urban form (The City is not a Tree" [1, 2]!). As a tree grows it preserves its characteristic form while undergoing over the years a huge loss in twigs (Johnson) [14]. Had it lost none of them over a ten year life then it would have them in the tens of thousands while a typical tree has only hundreds of twigs. Those which survive a year increase their probability of survival with each subsequent year and influencing even more the pattern of further growth. In this sense we can see Cheapside as a branch of the urban tree surviving from roman times through the catastrophes of the Great Fire of London and bombing in World War II when lesser thoroughfares lacking its functional importance perished. All trees of a species bear a resemblence to one another but we can only speculate about whether the alternative developments that could have taken place on the banks of the Thames would have looked like the city standing there today.

Our modelling process provides a basic mechanism whereby we can begin to address these issues and incorporate through simulation a sense of historical development as well as opening up the discussion of design aesthetics.

3 Townscape

We propose an urban modelling system whose aim is to create urban form on a scale equivalent to a town centre or small settlement at a level of detail showing variation in size (frontage, height and depth) of individual buildings. In this it is equivalent to the work Hillier, Brown et al referred to above and to that of Erikson [10] in that it recognises and defines a basic unit of structure in a building with specific size and orientation. It differs from these in that the underlying generating process takes less account of the influence of immediate neighbours in determining the characteristics of a unit and allows near (and not-so-near) neighbouring units to display similarities. In this it moves towards the inclusion of global rules for generating new points as in the work of Batty and Longley. At this scale we are beginning to make the transition from architecture and townscape to urban geography. This modelling process produces townscape while retaining formative links with the other two aspects. It is distinct from the other work in that it builds up the urban structure through the recognition of structural elements as part of townscape. Townscape embodies a basic recognition that buildings influence our perception of their neighbours design by their proximity. Our process recognises this proximity relation.

3.1 Background to the modelling process

Underlying the generation of urban elements is a model which aims to breath some life into the townscape. That is to make it interesting in appearance and possibly at the same time attractive to look at. In 1933 the mathematician C D Birkhoff proposed a theory of aesthetic value to the effect that works of art should be neither too regular nor full of incessant surprise [5]. If variations in a commodity which having attracted our attention are soon seen as regular we quickly lose interest as there is little or no new information to be gained from listening, say, to the ticking of a clock and our attention can be better deployed elsewhere. On the other hand variations which are too irregular prevent us making any sense of them, their information content is low and we find them confusing. Tuning our television sets outside the range of a transmitting station results in the reception of background noise which soon becomes both intrusive and unpleasant. An interesting discussion on this psycho-acoustic phenomenon is contained in Gardner where the analogy is persued in musical terms. Using analytical methods familiar to the telecommunications engineer Voss & Clarke [23] demonstrate that an analysis of changes or timing intervals in fine music (J S Bach, First Brandenburg Concerto) displays a particular distribution which is consistent with the Birkhoffs ideas. Voss has also suggested a relatively simple means whereby one can generate data fitting this distribution and which can be quite readily programmed using a computer language supporting recursion [11, 20]. A description of AutoLISP code to implement this technique is given in the Appendix. It is important to emphasise that the analysis of music no way implies that the reverse case holds true and that while this distribution may be a necessary it is by no means a sufficient criterion for achieving aesthetic value.

3.2 Creation and analysis of form

We adopt the generative method proposed by Voss to create models of urban form and then study these using the analytical approach of Voss & Clarke. In addition to offering a visual comparison between the generated forms in the townscape and actual examples we also use the analytical technique to test the hypothesis that the generative modelling process is suitable for the production of attractive and interesting townscape where the generated built forms are viewed in relationship to each other. To do this we apply the analysis to both the output of the generator and to actual examples of townscape to see if the results support the more intuitive conclusions made by visual inspection.

3.3 Generation

The modelling process operates at two levels. Firstly there is a general explicit rule equivalent to Brown & Johnsons second rule that buildings are developed contiguously along a street unless there is a specific decision to break the run of the block and secondly a decision is made as to what measurable elements within the townscape are allowed to vary. We have chosen to generate and vary the size of the following elements:

width of frontage
depth
height
number of built elements within a block
angle of orientation of one building to the next
angle of orientation of one block to the next.

There are two small deterministic items of architectural detail in that the orientation of a gable roof is allowed to vary being either parallel or at right-angles to the line of the frontage depending on the relative dimensions of the building in plan and the line of frontage may be offset from that of neighbouring properties as a result of programming descisions made determining the sequences of construction.

The computer program driving the modeller generates a different number sequence for each of the elements listed above and each sequence is retained and expanded until the model is complete. In this case we generated six sequences but could have increased this as further variables such as type and pitch of roof can be added to the model.

These sequences all vary in the manner proposed above, that is they are neither too regular nor too prone to instability in the form of large numbers of random fluctuations. Each sequence is independent of the others and contains only numbers generated within its own pre-set range limits. Also the characteristics of each range can be changed further by altering the parameters of the program model. The purpose of these parameters and their function is explained below.

3.4 The generative procedure

The aim of a generative procedure is to emulate features of those natural processes that are known to possess the required behaviour pattern. The best-known example comes from electronics is contact noise or flicker noise', it is a troublesome phenomenon generating low frequency noise under operating conditions and its precise nature is not fully understood. The power of the noise produced in this way increases as the frequency decreases, rising with the reciprocal value of the frequency [18]. Robinson [19] describes an analysis of flicker noise based on a combination of different random processes characterised by exponential decay. Schroeder [20] provides a recursive formula which allows us to use a computer program to combine these processes. It is fairly straightforward in principle although somewhat mathematical in nature and is described in the Appendix. Rather than introduce more mathematics than is absolutely required into the account we have chosen to concentrate on a mathematically much simpler approach which is conceptually superior and almost as effective.

We use a simple and very practical procedure proposed by Voss and described by Gardner [11]. While it is eminently suitable for implementation through a computer program it can be carried out if necessary without any computational device at all. The procedure is as follows:

Take a small number of dice, say 4, and preferably coloured for easy identification.
Arrange the dice in order in a row from left to right, red, blue, green and yellow.
Throw each die and add all four numbers thrown.

Then throw the dice in an order given, for example, by the table below where each row of the table represents a turn and only those dice which have a 1 in their column are thrown during that turn.

At the end of each turn the numbers on all four dice are added together to make the score for that turn.

At the end of the table the cycle is repeated as necessary.

Dice	Red	Yellow	Green	Blue
Turn 1	0	0	0	1
Turn 2	0	0	1	0
Turn 3	0	0	1	1
Turn 4	0	1	0	0
Turn 5	0	1	0	1
Turn 6	0	1	1	0
Turn				
	1	1	1	1

Table 1

Each die in the table may be taken as representing one of the constituent exponential processes mentioned above. The following sequence is typical of the figures generated at successive turns: 17, 16, 10, 9, 16, 13, 21.

These numbers may then be used to dimension successive constructions within the model. The computer will generate a number of independent sequences, one for the width of frontage, one for the height of the building etc. Because the program which produces each sequence is recursive it must be capable of pausing in each sequence to return to or take up another sequence. Each sequence of numbers is modified to fit a particular range and suit a particular purpose. For instance the angles by which one building is oriented differently from the next is small so the generated number is multiplied by a scaling factor less than one. Likewise the scaling factor is increased for the angle between blocks of buildings at road junctions.

The main parameters of the program correspond to the number of dice used, the number of faces on the dice and the repetition factor in throwing. In the table above the repetition factor is 2 as the blue die is thrown on every second turn and green die is thrown once for every two throws of the blue one etc. As with normal dice the number thrown lies randomly anywhere between 1 and 6 and there are 4 dice. These can be varied to throw the green die on every third throw of the blue and for each of 8 dice to have 12 (!) equiprobable aces. We use the notation (4,6,2) to indicate 4 dice with numbers up to 6 on each of 6 faces and that the pattern of dice thrown changes every second throw. Likewise (8,12,3) represents 8 dice, face numbers up to 12 and change of throw pattern every 3rd time.

The program allows experimentation, the greater the number of dice the greater the range of numbers which can be thrown, the smaller the number of dice the wider the percentage variation (more random and unpredictable) the number sequence. The numbers generated cluster about a mean with a normal distribution. In the case of 4 dice with six faces the possible numbers in the sequence range between 4 and 24 and cluster about an average value of 14. Although this is a useful indicator of the functioning of the program the real significance of the process lies in the sequencing of the numbers. The table above is important in that determines the sequence and the possibilities of change on the next throw. A listing of the relevant parts of the AutoLISP program we used to implement the procedure is given in the Appendix.

4 Analysis

The input to the analysis procedure is the sequence of numbers which were either generated in succession by the computer program or measured from a range of contiguous, or nearly contiguous, actual buildings. In the case of the generated numbers these are used in a model to define the width of frontage, say, of the buildings and in the case of measurements they would be taken from a sequence of frontages and made either on site or, as in this study, from maps.

The analysis involves transforming the data mathematically using the Fourier transform process. This is more familiar to telecommunication engineers than it is to architects so we attempt a brief explanation of what it is and what it does.

An input signal to a microphone or radio transmitter broadcasting music rises and falls, varying with time. In this respect it is like the number sequence generated by our model. 7e electronic equipment used must be capable of handling a wide range of notes of different frequencies during the performance o the music. Fourier analysis allows us to determine what the frequencies of these notes are and what proportion they make up of the total broadcast. In this way we gain two different perspectives on the same thing one being the piece of music as we hear it over time and the other is the perspective of the broadcast engineer who must match the capabilities of the transmitter to the qualities of the signal. It is a perspective of this second kind which we seek in relation to the performance of our model and which will allow us to establish a measure whereby we can compare the output from the model with actual examples of townscape.

Clearly if we do this we are not talking about the pitch or frequency of musical notes but about something closely analogous within the spatial domain. It is important to remark here that as in the broadcast example the time dimension disappears from our considerations entirely then so too does the spatial arrangement of our buildings and we are left looking at an overall statistic whose behaviour relates to the generated or measured urban area as a whole. This is because as in the broadcast music example the sounds are generated in a temporal sequence so also are the generated buildings arranged in a spatial sequence.

Referring again to our musical analogy, a particular instrument produces a characteristic sound or waveform varying in time and this waveform is produced by combining a number of different frequencies or pure notes. It is this ability to deconstruct a sound wave into its constituent frequencies that is the foundation of Fourier analysis. The technique we use is the Fast Fourier Transform (FFT) which is a mathematical technique particularly suitable for use with digital computers and is therefore of value to us too. What makes it especially suitable for our purpose is that it takes its input in the form of a series of numbers which in our musical example represent the strength of the broadcast signal at any particular time and at regular intervals thereafter and which in our townscape measure a feature of the design in successive buildings. We do not thus move steadily through space in equal steps but one building at a time where the spatial step is determined by the size of the building which is itself dependent on the actual measurement being input. Just as the FFT needs to sample music at equal time intervals it takes its spatial data one building at a time, moving in equal steps through a sort of building space rather than real measured space. The picture that we gain from using the FFT in this way is one which refers the buildings and their relationships to one another and this constitutes townscape rather than urban structure as we would measure it on a map.

If all buildings in a townscape had the same width of frontage then apart from being an exceedingly boring example of urban design it would produce an Fourier transform for the building width of one well-represented spatial frequency. We analysed not only the output from our model but examples of real and conventionally very attractive townscape and also included public housing estates.

At the other extreme if the width of the frontages were to vary entirely at random then we have an example of a limiting case where all widths are equi-probable and the output of the transformation could include all possible frequencies.

Between these two cases lies another where the width of one building differs from that of its preceding neighbour in the number/street sequence by one unit and where the change is randomly chosen either positive or negative so that a typical sequence of widths could be: 1, 62, 63, 62, 63, 64, 65, 66, 65, 64, 63, 64, 65, 64, 63.

In this type of sequence the width of one proper is strongly influenced by the

preceding one as it a persistent memory were retained and slowly disappears to be replaced by that of succeeding elements. This is better known as the phenomenon of Brownian motion, the movement of pollen grains at a microscopic scale from position to the next. The Fourier transform of a Brownian sequence results in the particular form of frequency distribution in Figure 1 where the slope of the graph with log/log scaled axes is -2.

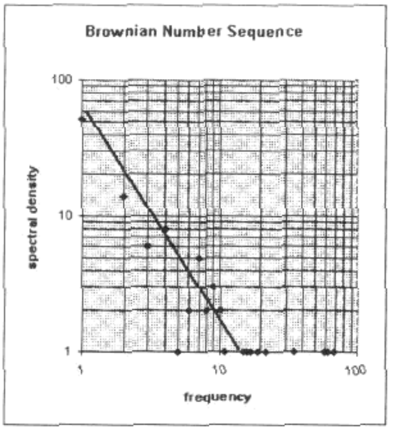

Figure 1 Power spectrum for Brown noise.

This type of graph has a mathematical expression of the general form:

f(x)=cxß

where c is a constant and the value of 1 measures the slope of the graph.

This general expression is known as a power law. In the Brownian case I=2 (Figure 1) and in the random example where the frequency plot tends to the horizontal 1=0 (Figure 2). The significance of power laws lies in their applicability to a wide range of natural phenomena, they are discussed more generally in the mathematical context of fractals and chaotic systems, Schroeder [20].

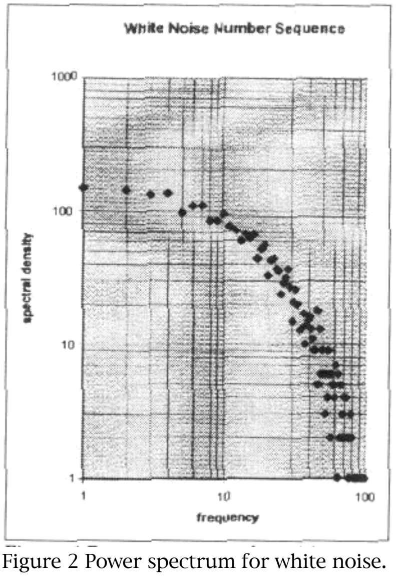

Figure 2 Power spectrum for white noise.

Between the near-predictability of the Brownian case and the entirely random, chaotic case known as 'white noise' (again by analogy with electronics) lies the region of interest defined above and identified by Birkhoff above where regularity and variation coexist. Voss & Clarke [23] argue that a value of ß = 1 represents a balance at which interest and also possibly aesthetic value are maximised. They have applied this to examples in the field of music and Chinese landscape painting. Here we extend this approach to the creation and analysis of townscape, both historical in origin, planned and computer-generated. We also tentatively extend the approach to include the characteristics of large-scale urban form on the scale at which Batty & Longley [4] work and more contentiously discuss the role of computer systems in the process of creative design.

5 The Experimental results

5.1 The vernacular

Figures 3 and 4 show the historic centre of the small town of Coggeshall in Essex and Figure 5 the frequency (power law) spectrum associated with the sequence of frontage width measurements made from the map. The slope of the graph g is close to the value of -1 as we might anticipate from the discussion above for an example of high quality townscape. This in effect sets a standard for our model to reach.

We applied the analytical side of our modelling process to Brough in Cumbria, a small Pennine village which is architecturally distinct from Coggeshall having a quite different vernacular building tradition. There is again a reasonable approximation to a slope 6 = -1 in Figure 6 although the scatter of points is more pronounced. This confirms that Coggeshall is not an isolated example and this is a useful result in the context of what follows.

Figure 3 Coggeshall town centre.

Figure 4 Map of Coggeshall town centre, Essex. Crown copyright, Ordnance Survey.

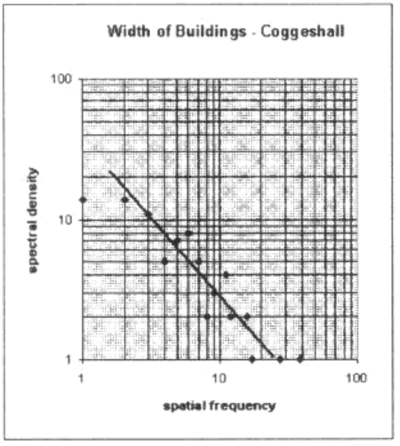

Figure 5 Spatial frequency spectrum for Coggeshall.

5.2 The generated model

An example of generated townscape is shown in Figure 7. On a cursory visual inspection this is comparable in its variety of building shapes and sizes with the Coggeshall case. The model uses a number of different number sequences and these all vary in their characteristics. The frequency spectrum in Figure 8 measures the strength (power) of the frequency components for a numerical sequence produced by the model (4, 6, 2) and again we find g to be close to -1 although there is a scattering of points about the trend line. This is repeated for other configurations of the model. This lends support to the view that the generative modelling process could produce at least an interesting and perhaps not unattractive example of townscape.

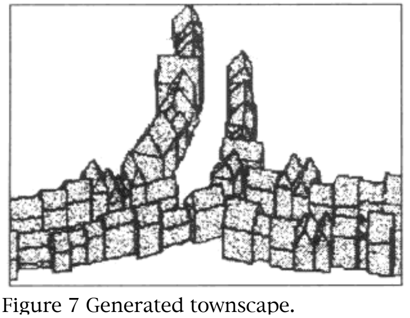

Figure 7 Generated townscape.

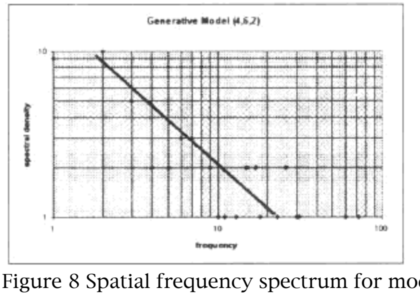

Figure 8 Spatial frequency spectrum for model (4,6,2).

The use of irregular (white noise) and largely predictable (Brownian) number sequences to construct very simple blocks of buildings. Clearly neither of these are likely to result in any form of attractive design and differ substantially in visual effect from that provided by the modelling process in Figure 9.

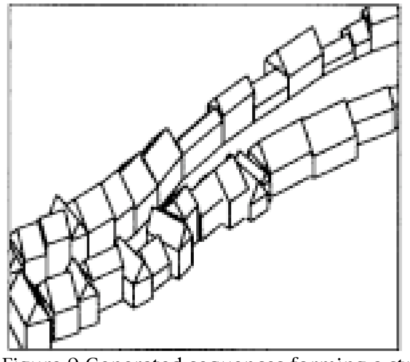

Figure 9 Generated sequences forming a street.

5.3 The modern

Finally we looked at three modern developments. The first is green field public housing on the outskirts of a small town and the second an area of modern office and commercial development within the City of London in the general area studied by Brown and Johnson.

5.3.1 The public housing development

The public housing consisted of standardised units fronting onto distributor roads. There was very little variation in size and similar units tended to be located next to one another with a change of size indicating a new house style which was then repeated. The fast Fourier transform failed to produce any output from the data supplied and we assume that this technique requires a minimum level in variation in order to work. Accordingly we resist the temptation to draw conclusions about the quality of townscape within public housing developments.

5.3.2 The City of London

Developments within the City of London, Figure 10 proved a more fruitful source of data. However, the graph, Figure 11 shows a wide scatter of points indicating perhaps that while there are many architecturally significant and notable buildings in this area the quality of townscape may not be that high. We have carried out separate analyses not shown here, of the nearby Moorgate and Clerkenwell areas of London and the results are similar to that in the City.

Figure 10 Map of part of the City of London. Crown copyright, Ordnance Survey.

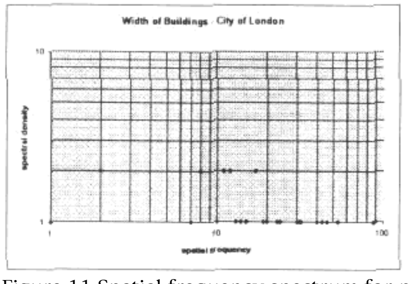

Figure 11 Spatial frequency spectrum for part of the City of London.

5.3.3 The neo-vernacular

The third modern example is a conscious attempt to create the appearance of the vernacular by Essex County Council who have applied policies to control development which explicitly favour emulations of traditional buildings and their settings [7]. The Council has concentrated its own design efforts on the new town of South Woodham Ferrers and particularly on its town centre, Figures 12 and 13, which is the final subject of our study. We hope to find out whether the new development compares in our analysis with the originals which inspired the policy in the first place.

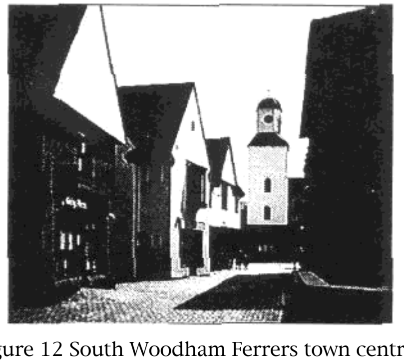

Figure 12 South Woodham Ferrers town centre, Essex.

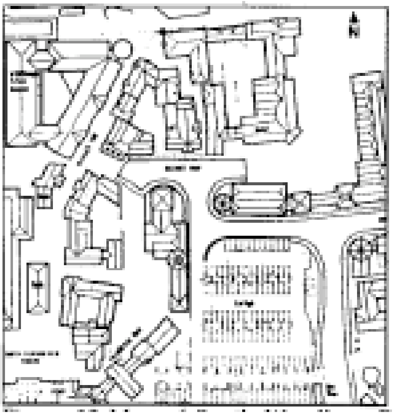

Figure 13 Map of South Woodham Ferrers town centre. Crown copyright Ordnance Survey.

A key feature of the neo-vernacular style is that it stresses the quality of townscape and it is because of this that an analysis of the South Woodham Ferrers town centre is of interest. Again the measurements taken are the widths of building frontages. In the case of historic settlements it is relatively easy to identify the building on a map and measure the frontage without having detailed local knowledge. However, in this case the townscape and the function of the buildings are not linked in the same way. It is not so easy when looking at a plan to identify functioning units as it is to spot design features. Indeed the townscape could, at least in theory, be independent of the functions lying behind the facade. Because there is a commercial imperative to provide well functioning properties to modern standards there is an ever-present risk that attempts to create an attractive townscape may disconnect from functional requirements.

As this is the kind of application where our generative model might well be used an analysis of the new town provides a useful indication of how successfully in design terms this mix of old forms and modem functions can be. As this is a design-led approach we have identified and measured the main design elements. An example occurs in the case of the superstore built in the form of a large medieval barn to which gabled frontages for office accommodation have been added facing onto the main square. These frontages are measured as independent elements which is what they would have been in a proper historical context.

A key issue in both measurement and generation is the accuracy of the measurements either input to the analysis or required as output from the model. The set of measurements made from a 1:500 scale map produced a rather scattered graph, Figure 14. The many different sizes of frontages influence the scatter of points on the graph. We decided to reduce the numerical spread of the measurements by halving them and rounding upwards to the nearest whole number. The effect of this is to group the design elements into a reduced number of size classes while maintaining the original sequence. The consequence of this simple procedure on the graph is quite dramatic as it is now almost exactly linear at ß=-1 with much reduced scatter, Figure 15.

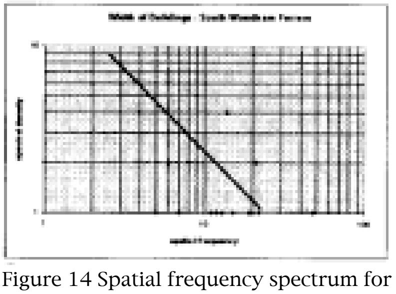

Figure 14 Spatial frequency spectrum for South Woodham Ferrers town centre.

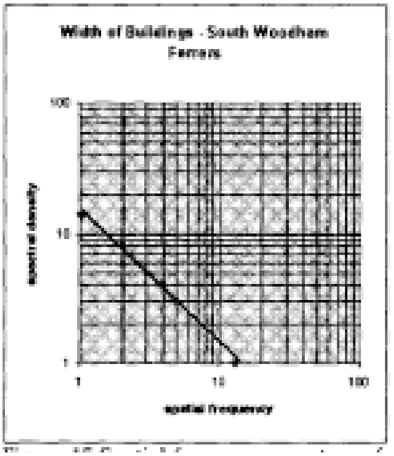

Figure 15 Spatial frequency spectrum for South Woodham Ferrers town centre using a coarser spatial scale

6 Interpretation

6.1 A basic unit of measure

We have effectively imposed a numerical restriction on the scale on which the measurements are made and it would appear that the new scale has had an influence on the form of the graph. In doing this we have in effect established a measuring rod for the development equal to double our original unit, a Modulor scale seems to have emerged from the analysis. A tentative estimate of the size of this unit in the case of frontage measurements in South Woodham Ferrers would be about 2.5 metres. Confirmation of the existence of such a unit, of its size and of the circumstances in which it would apply requires further investigation over many more cases.

On the basis of this single set of measurements and the linearity of the second graph the designers of the town centre may feel pleased with their efforts. Having established that a unit of measure seems to be inherent to their design they could procede to apply this in further work.

If we use the model to generate form the same considerations will apply. If we use settings of (6, 6, 2) rather than (4, 6, 2) we increase the range over which numbers in the sequence can be generated by 4 times while in the case of (8, 12, 2) it would be 32 times as great. By increasing the set of numbers that we can generate it is less likely that any given number will be chosen and that consequently the graph will be more scattered and less linear (I = -1). Thus few numbers only generated using an extensive range are less likely to produce sequences which display the design (interest) and graphical (linearity) criteria we seek than if we generate many from a more restricted range. It seems we need to generate a sufficient quantity of units within the same size class to produce the linear graph plot and to allow us to perceive the balance between regularity and variety in the design.

The model interacts with the user at the start of each generation by requesting the input of parameters, (number of dice, number of faces, repetition factor). This has been a largely experimental process but we have become aware that the choices made here can have a noticeable effect on the emergent forms. In general we have used lower figures for all parameters as when we experience townscape there is a limit to the number of buildings we can see and thus a limit to the range of possible sizes which allows them to be distributed in an interesting manner. By using larger numbers to generate the widths of buildings located in blocks only a few buildings long the effect was closer to randomness than visual interest.

The emergence of a Modulor-type unit of scale suggests that both the generated data and the urban structures could possess a scaling property and fractal dimension. If we measure from two maps one at a larger scale than the other there comes a point for an particular group of buildings at which the coarser measurements and linear grap disaggregate and scatter. There is a similarity here with the measurement of coastlines and derivation of the fractal dimension [17, 20].

6.2 *Extending the approach to the larger scale?*

Typically towns and cities are characterised by a mix of uses. The application of the model was extended to represent different uses for the buildings created signifying them by different pen colours. In establishing the parameters for the run we presently limit the range of numbers to correspond to the size of the settlement being generated. The frequency with which the various uses occur is given by the power law graph and as the underlying process for generating the uses is identical in its nature to that used to produce the dimensions of the model we will expect to see a slope R = -1 as before.

This type of graph has been noted in the context of urban geography [26] in the rank-size relationship between a city's size and its ranking where in its idealised form the second ranked settlement has half the population of the first, the third-ranked one third and so on, Figure 16. The highly structured spatial urban hierarchies of Christaller and Lösch are broadly consistent with this distribution [15]. As these hierarchies are functional in origin we draw attention to the possibilities of general principles underlying growth of settlements and affecting both their functional relations, structure and townscape. It is possible to show [12] that all the terms in an idealised and infinite rank-size sequence can be built up without duplication from an infinite number of independent geometric sequences. This approach parallels at a simpler mathematical level the flicker noise analysis [18,19].

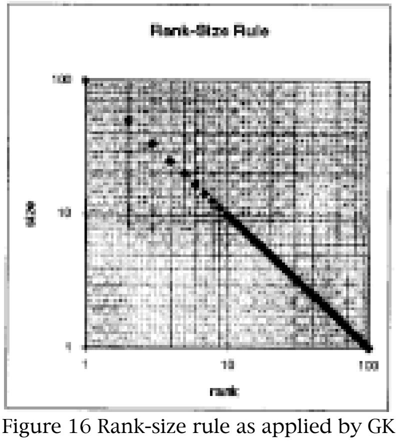

Figure 16 Rank-size rule as applied by GK Zipf to settlements.

6.3 *An alternative analysis*

An interesting alternative approach to the analysis of creative work involves the Poisson distribution [16]. This work aims to explore linguistic structures in the same way we have examined visual ones. Linear-scaled plots of our data, Figures 17 and 18 do in fact resemble the characteristic rise and fall of the Poisson distribution for both generated and measured data.

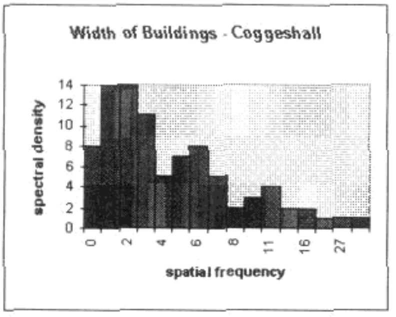

Figure 17 Spatial frequency spectrum for Coggeshall showing Poisson- like distribution.

6.4 The possibilities for design

Our aim is not to suggest that these procedures for generating form are a highly developed design tool, far from it. Instead it seems to represent only a fundamental level at which aesthetic appreciation begins to operate. There is often a large gap between the effort put into the detailed architectural design of buildings and their incorporation into their surroundings which good, bad or indifferent are a given of the site. That attractive townscape arises so often without a conscious design input and over an extended timescale that exceeds any individual construction time we believe indicates the presence of an underlying process which our analysis goes some way towards identifying.

This kind of process leading to design is not unknown. It occurs in nature. Professor John Maynard Smith recently illustrated two clear examples. The bee orchid has a striking visual design which is the result of symbiosis with a bee. The similarity of the flower to the bee is so great that the insect attempts to mate with the flower. This design has appeared as the result of processes operating over evolutionary time. Likewise cooperating termites manage to construct a highly functional mound which provides them with ideal conditions of temperature and humidity in which to live co-operatively together. As unlikely a Creationist as J B S Haldane was induced to write in a similar evolutionary context that "If *insects had hit on a plan for driving air through their tissues instead of letting it soak in, they might well have become as large as lobsters,* We seem forced to use language in this way to describe certain ideas effectively when the are located on at the edge of our knowledge and experience. This is especially true where it impinges upon our own ability to think and design.

Consequently we see our generative process as a relatively simple example of a class of emergent evolutionary processes. If our generative process is capable of design then for that design process to be improved upon then that the process must expand to include feedback. This feedback must be more than the simple symbolic language embodied in the chemical messages passing between termites. It must include a formal language with the ability to embody structures for its own modification. Evolutionary processes act only very slowly when the levels of interaction are as limited and as prone to chance as those between flowers and insects but fast and reliable forms of communication speed up the process of design exponentially. At their highest level they possess the power of thought.

We believe that it is in this area of communication and language that effort to develop CAAD should be concentrated in order to move from the chance-prone processes that have given us our present townscapes to one capable of detailed design solutions without constantly requiring our intervention and representing a waste of increasingly valuable human resources.

7 Conclusion

The modelling process presented here represents a first stage in the independent generation of creative design by computer. It is limited to emulating the forms of townscape and urban structure but we believe it has the potential for further development both in its theoretical underpinnings and as a practical generator of townscape taking into account topographical features and form. Because the aesthetics of architectural form are more highly developed and complex than those of townscape the task of extending this approach to generating aesthetically pleasing architecture is that much more complex but we believe theoretically possible. Related work in linguistics suggests that common ground could be established through creating formal language structures as a basis for further development.

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It also is important that we acknowledge the role played in this area by B Mandelbrot whose 1983 book is a wide-ranging and comprehensive description of the role mathematics plays in the description of a wide range of natural phenomena and behaviour. The chapters on the generation of fractal landscape models by computer and the studies of river systems are of particular interest to anyone working in this general area and clearly explained. His work has proved an inspiration to the mathematicians working in this area and whose efforts we in turn acknowledge.

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10 Appendix

A.1 A generative formula.

Schroeder [20] suggests the following formula for use in computer models for the generation of' 1/f noise as a more mathematical alternative to the dice model.

$$x_{n+1} = px_n + r_n \sqrt{1-p^2} \text{ where } x_0 = 0$$

p is the correlation coefficient between adjacent samples and rn is a random number with zero mean.

Like the dice model this requires that the computer's programming language support recursion.

A.2 Analytical and Generative Software

The link between sequential data and the graphical output shown here depends upon the Wiener-Khinchin theorem used in telecommunication theory. We used the Fast Fourier Transform function of SPSS v.6 running on an IBM PC clone and AutoCAD v.10 with AutoLISP running on an Apple Macintosh for the generative model.

A.3 Random Number Generator

It is necessary to generate a random number in a given range whenever dice are thrown in the model. This is the generator used in AutoLISP.

```
;------- RANDOM NUMBER GENERATOR - Dice 1-6---
;
(Defun RANDICE (/ x z r rn)
                (Setq   bot 0.500001
                        top 6.5)
                (if (not seed) (setq seed 757))
                (setq x (1+ (* seed 2197.0))
                        z (fix (/ x 4096.0))
                        seed (fix (- x (* z 4096.0)))
                        r (* (/ seed 4096.0) (- top bot))
                        rn (+ bot r))
                (If (> (rem rn 1) 0.5)
                (Setq rn (+ rn 1)))
        (Setq IntOut (fix rn)))
;--------------------------------------------------------------
```

A good practical generator of random numbers should not repeat itself in any displayed characteristic over the run-time of the model. In this it appears to be a reasonably fair example of its kind although being necessarily deterministic in nature it will eventually repeat itself.

A.4 *Throwing the Dice Recursively*

The following routine is at the basis of the model.

```
;------------------------------------------------------------------
;THROW
;The routine which is used recursively when multiple dice are thrown.
;------------------------------------------------------------------
(Defun THROW (numDice / ThisDie)
        (repeat numTurns
;Numturns is the number of times a dice
        (Setq ThisDie 0
is thrown before
        DCount (1+ DCount))
        (If (= Step SetStep)
        (Setq ThisDie (RANDINT 6)
;throw a number between 1 and 6
        ListDie (List ThisDie)
        DiceList (APPEND DiceList ListDie) ;Throw is placed into list
        Total (+ Total ThisDie))
;which is totalled)
        (Setq ThisThro (+ ThisThro ThisDie))
        (If (> numDice 1)
(progn(THROW (- numDice 1))
;throw remaining dic)
(Progn
(If (= Step SetStep)            ;
record variales when all dice thrown
(Setq NewRand Total
Dthrown DCount
hatThro ThisThro))
(Setq ThisThro 0
        DCount 0
        Step (+ Step 1)))
(Setq Total (- Total ThisDie))
        ;records and remembers partial throw
        (If (= (- Step 1) SetStep)          ;
        totals needed for accounting during
        Setq DiceLeft DCountexit from recursion.
emTotal Total))
(Setq ThisDie 0)
```