



senseable city lab:...

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Urban infoscapes: new tools to inform city design and planning

Urban texture has a profound influence on environmental quality. The ability to scan maps into a computer and manipulate them provides a new method of informing this aspect of urban design.

Urban infoscapes: new tools to inform city design and planning

Carlo Ratti and Nick Baker

During the past decades, many computer tools have been developed to assist in the environmental design of individual buildings. Heat, light, sound and especially energy consumption can be analyzed in many different packages. This is not generally true for urban design, especially at the medium scale. Although it is widely assumed that urban texture – the pattern of streets, building heights, open spaces and so on – will determine environmental quality both in the buildings and outside, tools for investigating the connections are sparse. The need for medium-scale understanding is confirmed by Givoni (1989):

'The outdoor temperature, wind speed and solar radiation to which an individual building is exposed is not the regional "synoptic" climate, but the local microclimate as modified by the "structure" of the city, mainly of the neighbourhood where the building is located.'

This paper describes how novel image-processing algorithms could be applied in urban areas to calculate a wide number of parameters. These parameters allow the construction of what we could call 'urban infoscapes': a layered collection of information on cities, that can be successfully used to inform urban design and planning.

DEM: a new format to store urban geometry

The research presented here started when we were scanning black and white urban maps of London, Berlin and Toulouse for graphic design purposes. It was then that we thought that these maps, which represented built areas as black and unbuilt areas as white, might be used for urban analysis.

Black and white urban maps are of course nothing new: they have been used in cartography for a long time. A famous example can be found in Nolli's eighteenth-century map of Rome (Nolli, 1747) [1]. A relative innovation, however, is the fact that these maps can now be scanned into a computer and manipulated – the digital format being conducive to a series of simple measurements. The first application one could think of is counting the number of white and black pixels on the image, thereby instantaneously deriving the ground

occupation coefficient. Other techniques might allow a more complex exploration of urban form.

The first idea was to adapt algorithms developed in the field of image processing to work with these black and white maps. Software was needed and the investigation began by downloading from the Internet NIH Image for Macintosh (2003), a free image-processing program. Many of the ideas in NIH Image will be familiar from popular programs such as Adobe Photoshop; the difference is one of emphasis. Photoshop is concerned mainly with visual appearance, whereas NIH Image concentrates on measurement and analysis. The basic data structure is the image, a 2-D array of pixels, each storing a single byte (8 bits), which is typically understood as an integer in the range 0–255. NIH allows any image to be modified and analyzed using a number of pre-defined functions. In addition, it can be customized with the introduction of extra user-defined functions. These functions are defined through macros, that is scripts containing sequences of operations in a Pascal-based programming language.¹



¹ A possible tool for urban analysis. Map of Rome by Nolli (1748), showing the area around Piazza Navona

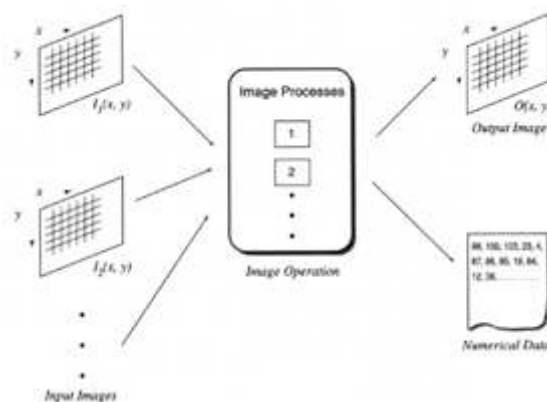
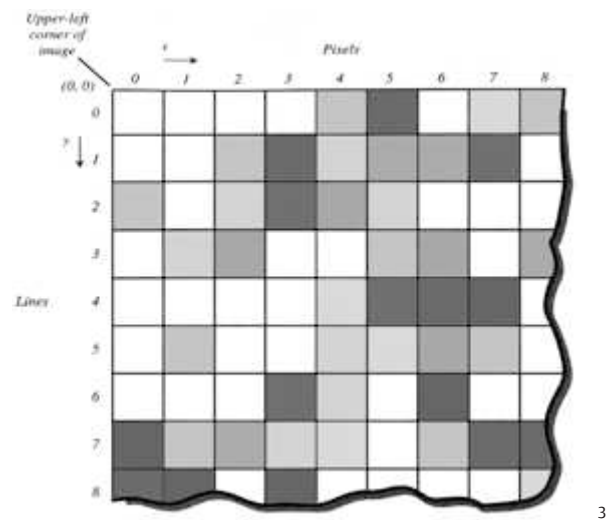
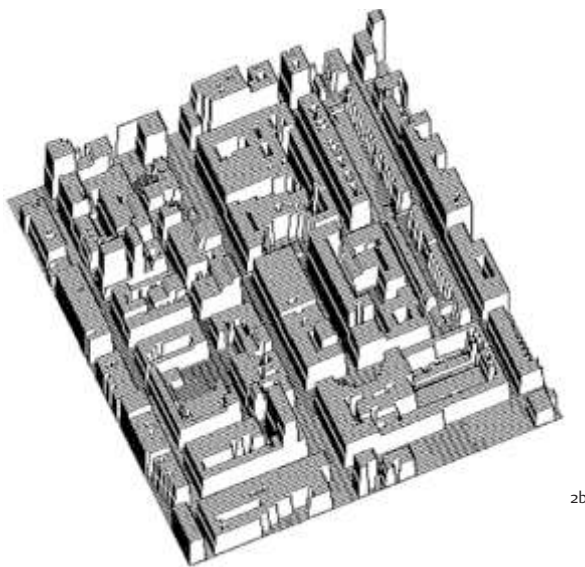
This potential encouraged us to modify the original black and white images to encode building heights. This resulted in producing what geographers call a Digital Elevation Model (DEM), an image where each pixel has a value proportional to its height, visually indicated by a grey level as in [2a] which represents a case study site in central London, around Tottenham Court Road. Although an image is a 2-D array of values, the DEM is equivalent to a full 3-D description of the urban surface. All the information that is contained in the axonometric view of London shown in [2b] or that can be encoded in any 3-D surface model, such as a CAD model, is also contained in the DEM image. In fact, automated ways

can be devised to switch from any one of these alternative urban representations to another.

The processing of DEMs

An urban DEM, as defined above, is a rectangular array of numbers which tells us the height of the urban surface (buildings and streets) at regularly spaced intervals. As such, it can be considered a digital image and analyzed with digital image-processing techniques.

A digital image is a collection of picture elements, or pixels, usually arranged in a rectangular array. A pixel is the smallest graphic unit of the image and, as an atom, it is not further divisible. It is assigned one



- 2 Creating a Digital Elevation Model (DEM)
 - a Case study site in central London in an aerial image (left), in a black and white ground map showing built and unbuilt areas (centre), and in the DEM format (right)
 - b Axonometric view of the central London DEM shown in Figure 2
- 3 The discrete pixel numbering convention that underlies a digital image
 - 4 A general digital image-processing operation which can be used to enhance both quality and information
 - 5 Computing shadow volume
 - a Urban profile (left) showing the procedure to cast shadows on a DEM: the repeated translation of the DEM with a simultaneous reduction of its height (centre) allows the detection of the shadow volume (right)
 - b The volume being in shadow on the London case study, represented on a [0..255] grayscale; sun position: azimuth=30°, altitude=30°.
 - c Shadow casting on the London case study DEM, sun position: azimuth=30°, altitude=30°.

or more numerical values, which define its appearance (colour, brightness, etc). The position of each pixel in the image is given by its co-ordinates, which specify horizontal and vertical location. They can also be interpreted as column and row and follow the axis sign and conventions illustrated in [3] – the pixel of co-ordinates (0,0) being in the upper left corner of the image.

The roots of digital image processing are generally traced back to the early 1960s, when the US National Aeronautics and Space Administration (NASA) started developing its lunar science programme. Video images had to be collected and transmitted to earth and this required the development of digital retrieving and processing techniques. Further developments in image processing occurred in the following years in the context of medical research and earth-orbiting satellites. Today, digital image processing has a myriad of applications in such different fields as biology, defence, photography, publishing, medical diagnostic imaging, remote sensing, space exploration, film special effects, astronomy, etc. In Baxes' (1994) words:

'this dynamic field truly touches us all, playing an important role in our world ... Digital image processing techniques are used to do everything from reading your checks at the bank to automatically inspecting the fill-level of your pop bottle.'

Image processing is exciting as it changes the form or appearance of an image through computerized, numerical techniques. Numerous and highly varied types of operations have been developed during the past 30 years: while one of them may improve the quality of an image, another may automatically extract information from it. Whatever the aim, the same steps are followed: a digital technique is

applied to an input image and a digital result, such as a new image or a list of extracted data, is output [4].

For an introduction to digital image processing see Jain (1989) and Baxes (1994). A discursive overview of the digital treatment of images can be found in Mitchell (1992).

An image-processing algorithm for shadow casting

Let us see how image-processing algorithms applied to DEMs could help in getting useful information about cities. Let's take a simple problem: how to cast shadows on a DEM. A program to address this problem was written at the beginning of this study to compute shadows for any angle of illumination and is briefly reviewed below.

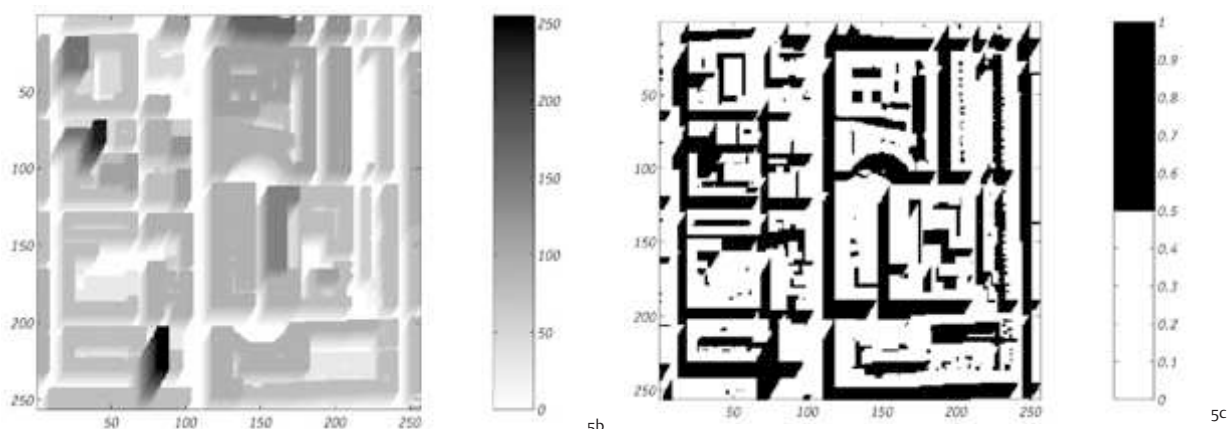
Two basic image-processing operations are required, which are both easily implemented in NIH Image:

- translation of the DEM in a given direction
- reduction of building heights, based on the subtraction of a constant value from the built parts of the image, while keeping the street level constant.

The approach taken is to compute 'shadow volumes' as a DEM, that is, the upper surface of the volume of air that is in shadow. We start by defining the three components of the vector pointing towards the sun. Then we compute the components of an opposite vector, scaled so that the larger of the x and y components is just 1 pixel, and the x component is adjusted to the image calibration. If we translate the DEM by the x and y components, and simultaneously reduce its height by subtracting the z component, we get part of the shadow volume. If we continue translating and lowering by multiples of this vector,

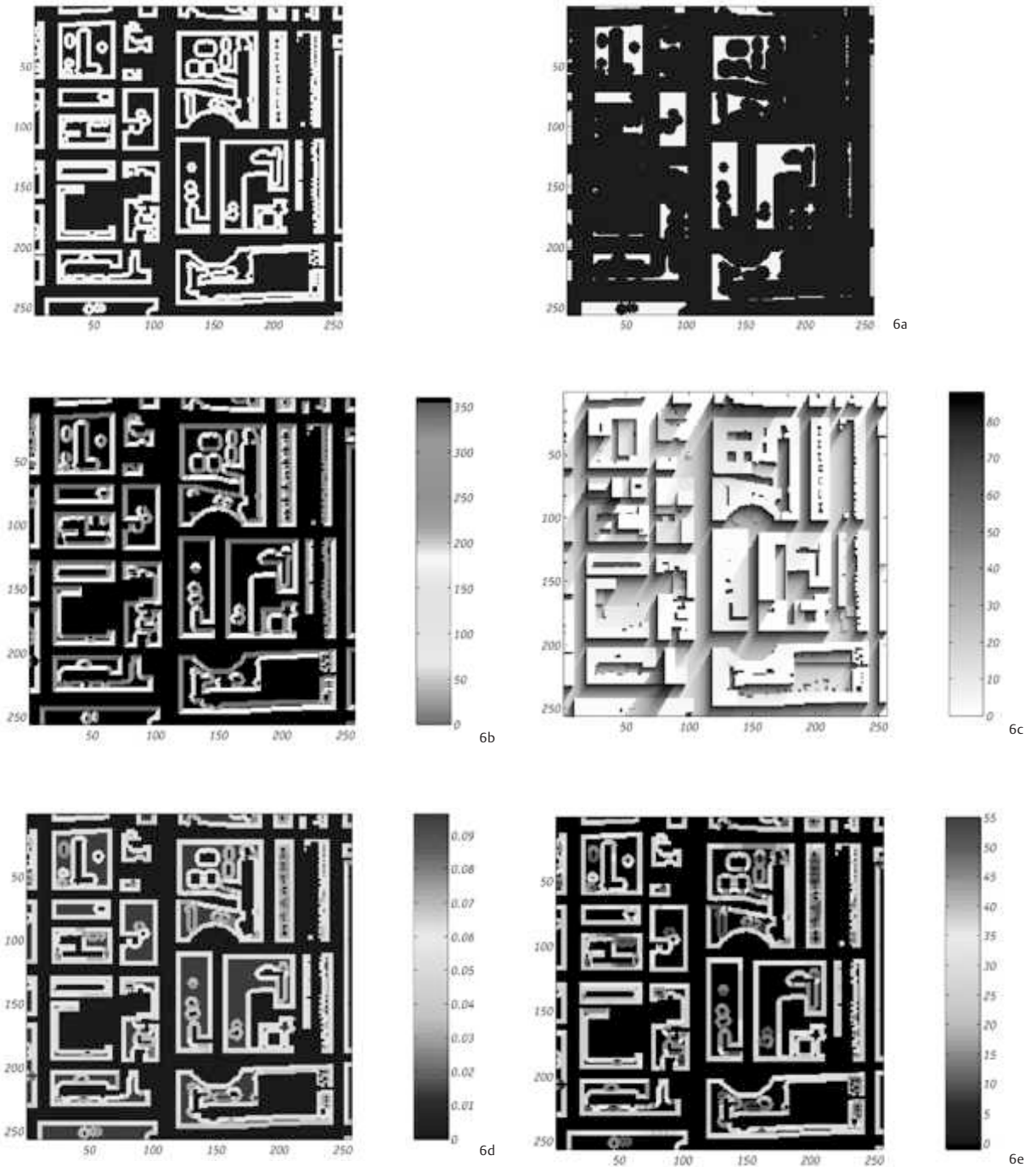


5a



5b

5c



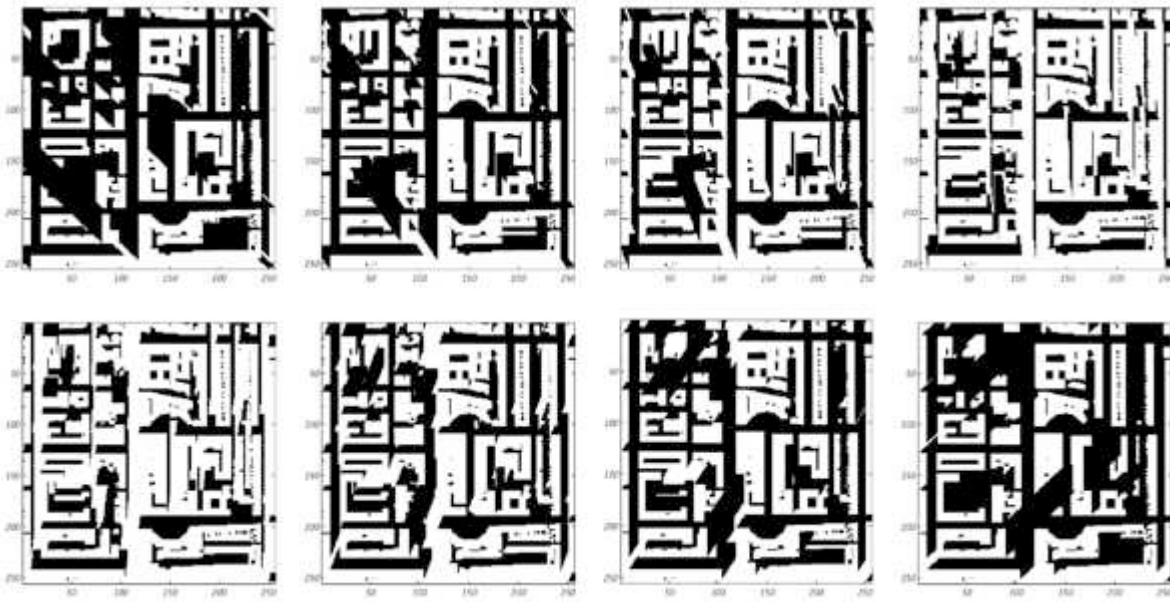
6 Exploring the effects of urban texture on building energy consumption
 a Passive (within 6m from the facade) and non passive zones (more than 6m from the facade) on the London case study, second floor
 b Orientation of passive zones on the London case study, second floor (slicing the DEM at height = 6m), obtained by filtering the image with the Sobel edge-detectors; facade values are spread

inside the buildings by assigning to each internal pixel the value of the nearest facade pixel; values in degrees
 c Maximum obstruction angle on the London case study DEM looking in the direction azimuth=30°.
 d Energy consumption on the London case study on the second floor (height = 6m); glazing ratio 50%; non-passive zones consume approximately

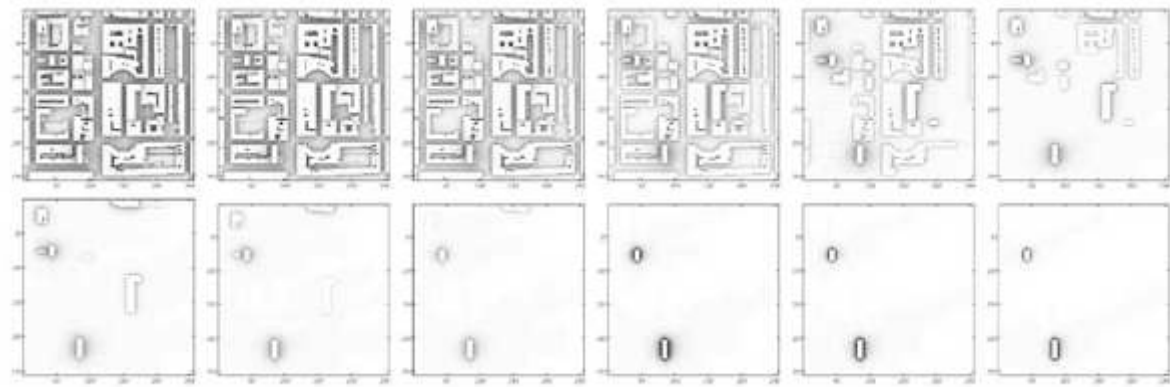
the double of unobstructed passive zones; values in [KWhm²year⁻¹]
 e Value of the optimum glazing ratio, which minimizes energy consumption, on the London case study, on the second floor (height = 6m); small courtyards and obstructed areas can reach glazing ratios as high as 50%, while less obstructed areas rarely exceed 30%; values in percentage [%]

7 Computing radiative parameters
 a Shadow casting on the London case study on 31 December, hourly intervals
 b Sky view factors on the London case study DEM computed at 0, 3, 6, 9, 12, ..., 33m; results were obtained by spreading 1000 fictitious 'sun-positions' on the sky-vault
 c Sky view factors inside the buildings on the London case study DEM,

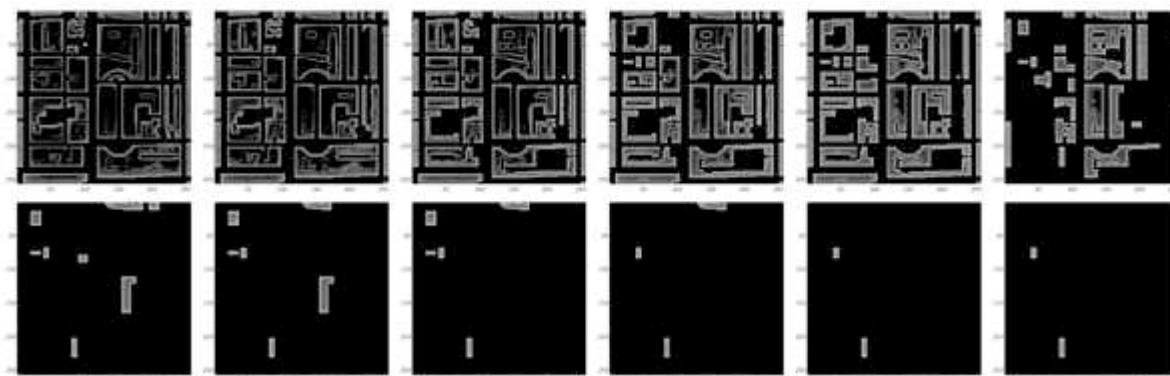
computed at 0, 3, 6, 9, 12, ..., 33m; results were obtained by spreading 1000 fictitious 'sun-positions' on the sky-vault
 d Experimenting with solar envelopes: the image represents the height of the surface where there are 1, 3, 6 hours of sun respectively (values for 31 December); on the far right the surface where there are 6 hours of sun is plotted in axonometric



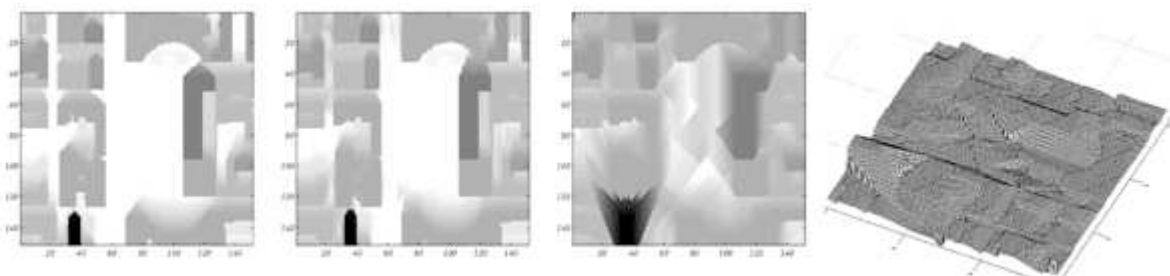
7a



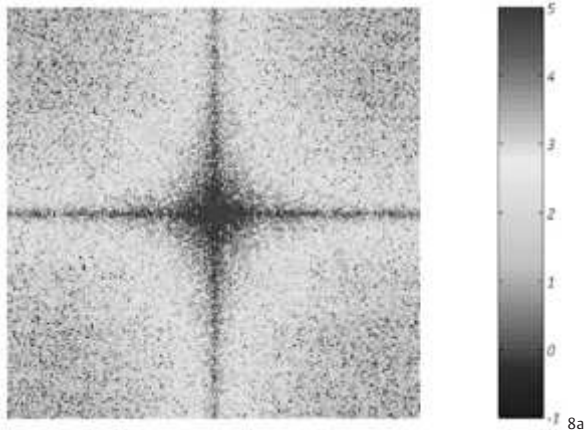
7b



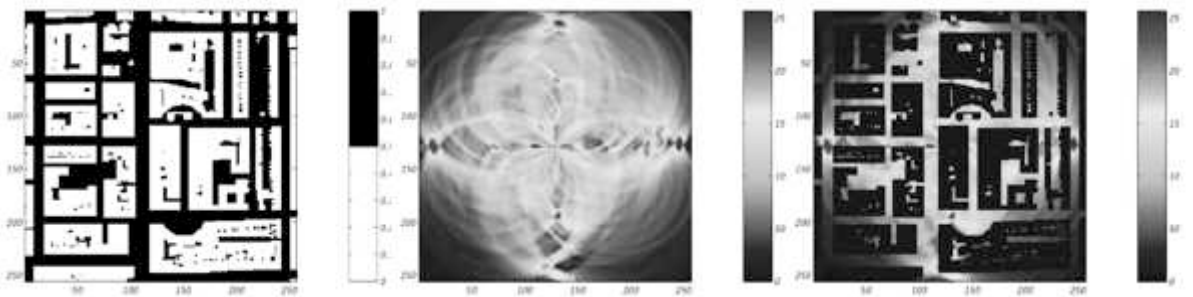
7c



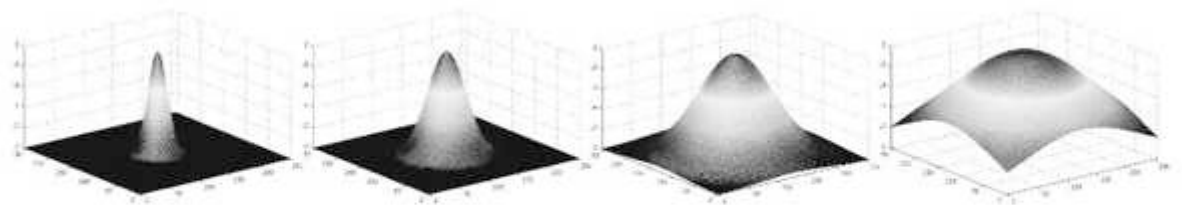
7d



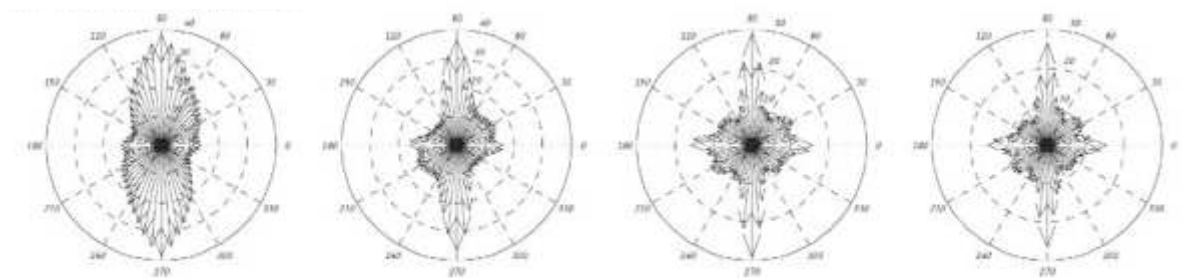
8a



8b

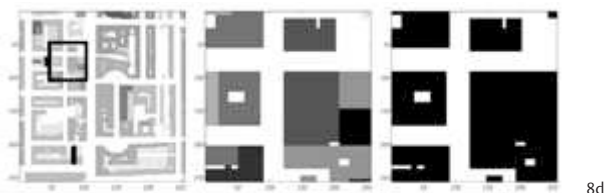


Gaussian-like decay function

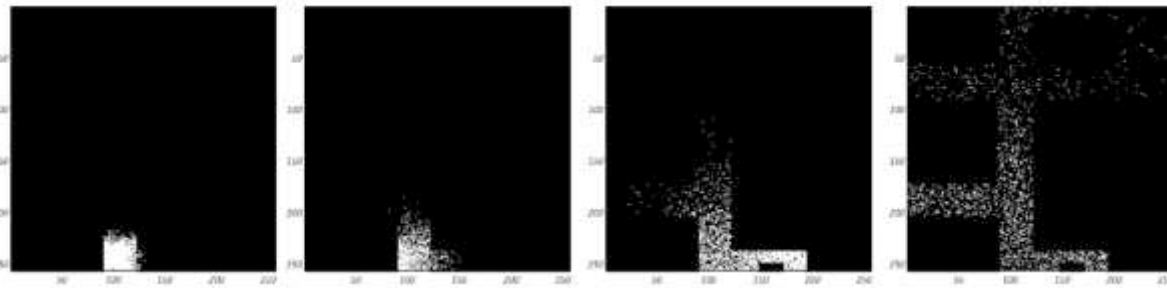


London

8c



8d



8e

8 Examining the interaction between city and wind
 a Directionality analysis: Fourier transform for the London case study. The plot shows the sum of the squares of the real and imaginary parts of the Fourier transform using a colour-scale
 b Directionality analysis. Left: black and white image of London; centre: Radon transforms in polar co-ordinates; right: both images superimposed. Note the precise fit of dark spots in the street network: they appear in each urban canyon at the point of minimum

distance from the centre of the image (as can be understood from the mathematical definition of the Radon transform). Therefore, from the position of these spots it is possible to have an idea of the directionality of the urban texture
 c Directionality analysis for the London case study weighted using the Gaussian-like decay functions plotted above. Note that not all the plots are to the same scale. From left to right: values of sigma 0.1–0.2–0.4–0.8 respectively
 d Selection of a sub-

portion of the London case study DEM (framed on the left image), which is then scaled (centre) and transformed in black and white (right). The latter image is used to channel a Cellular Automata for noise-driven diffusion (figure 6.39)
 e Modelling noise-driven diffusion on a selected portion of the London case study using Cellular Automata. A pollution source is positioned at the bottom of the image, while pollutant particles migrate upwards. Diffusion after 10, 100, 1000 and 10,000 iterations

Illustrations [6] to [9d] present how the analysis of DEMs with image-processing techniques allows:

- Exploration of the effects of urban texture on building energy consumption. This includes the identification of all building areas that are within 6m from a facade [passive areas, 6b and c]. An established computer model to calculate energy consumption in buildings, the LT Model (Baker and Steemers, 2000), has been coupled with the analysis of DEMs, providing energy simulations over extensive urban areas [6d and e].
- Exploration of a number of image-processing techniques to compute radiative parameters on a DEM. These include shadow casting [7a], sky view factors inside and outside the buildings [7b and c], and solar envelopes (as defined by Knowles, 2003, and Capeluto and Shaviv, 2000) [7d].
- Examination of the interaction between city texture and wind. This can be done either via a number of geometric measures of urban porosity and anisotropy [8a-c] or Cellular Automata modelling where pollutant dispersal, for example, can be simulated by giving simple translation rules to 'digital smoke particles' [8d and e].
- Calculation of parameters to complement Space Syntax, a well-known method for studying urban configuration which has been developed by Professor Bill Hillier at University College, London (Hillier, 1996). A number of alternative indicators of the accessibility of urban areas can be developed, based on their visibility [9a-c] and accessibility [9d].

and take the maximum of this volume with that previously calculated, we build up the whole shadow volume [5a]. The process can be stopped when all levels are zero, or the translation has shifted the volume right off the image.

Results can be seen in [5b], which represents shadowing on the London case study. To reduce the shadow volume to an actual map of shadows on the roofs and ground of the city, the original DEM is subtracted from the shadow volume. Pixels with negative or zero value are in light, positive values are in shade, as in [5c].

This algorithm is very simple and impressively fast. The running speed depends on the number of pixels in the image, but not on the geometric complexity. So it is feasible to process acres of city at a time, something unthinkable with traditional geometric models.

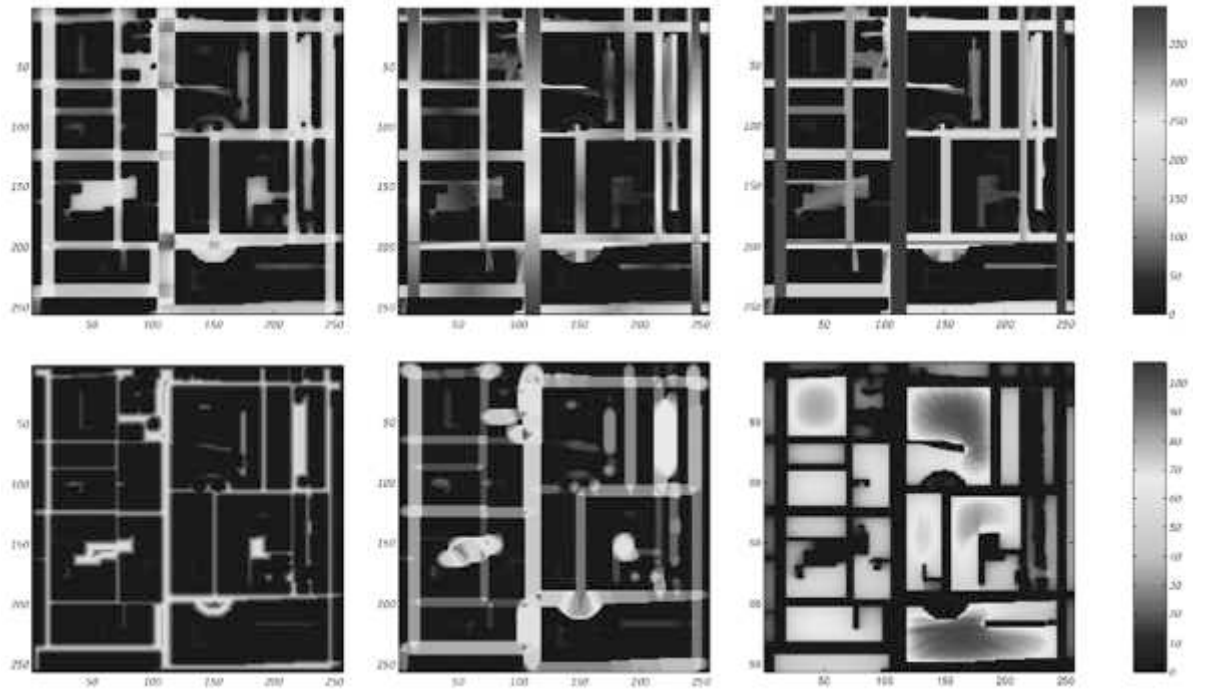
A library of analysis functions

Based on the same approach, a whole library of functions to analyze urban texture can be built. A number of different results is shown here to make a proof of concept of the wide range of possibilities that open up by using urban DEMs. For more detail on the algorithms that have been written or on their relevance to the urban context, the reader is referred to Ratti (2002).

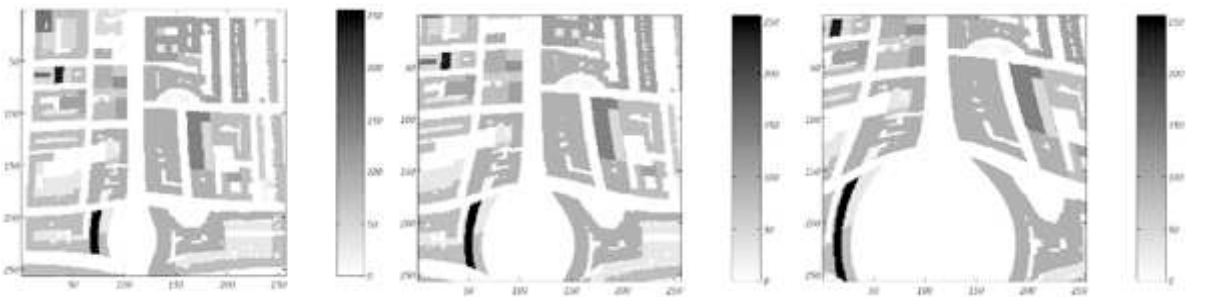
Using these techniques in design

Different analyses of urban DEMs were briefly reviewed in the above paragraph. Images shown range from the computation of energy consumption in buildings to the assessment of sunlight and daylight on facades, the potential for pollution dispersion in urban canyons, and the analysis of the accessibility of streets based on Space Syntax. While these techniques are perfectly justifiable on their own as a contribution to the characterization of urban textures, a more fundamental question is raised: could the analysis of urban DEMs help in the design of cities? Could it be of any assistance to the planner and the architect?

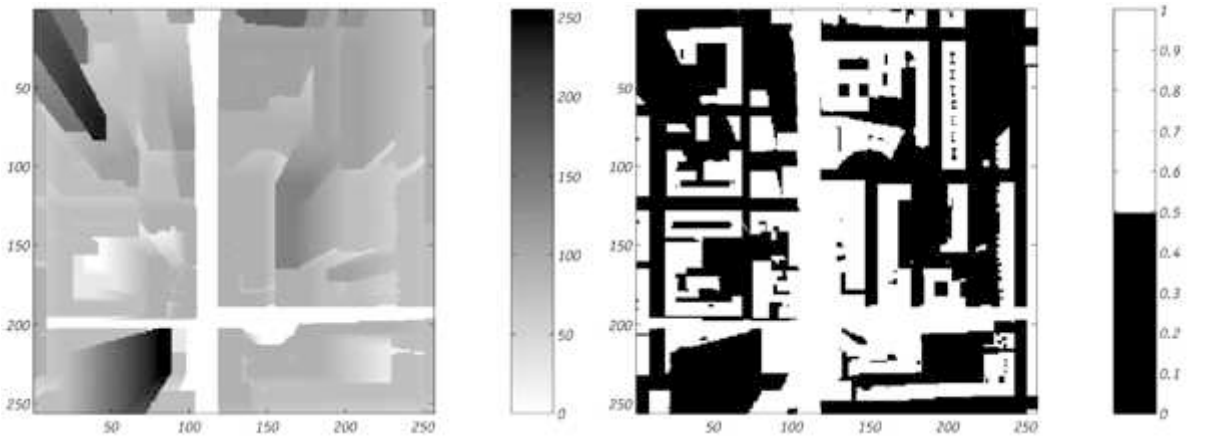
Some tentative and preliminary answers to these questions are given in this paragraph, which also



9a



9b



9c

9 Calculating parameters to complement the Space Syntax urban configuration method
 a Lines of sight analysis on the London case study DEM (32 different directions

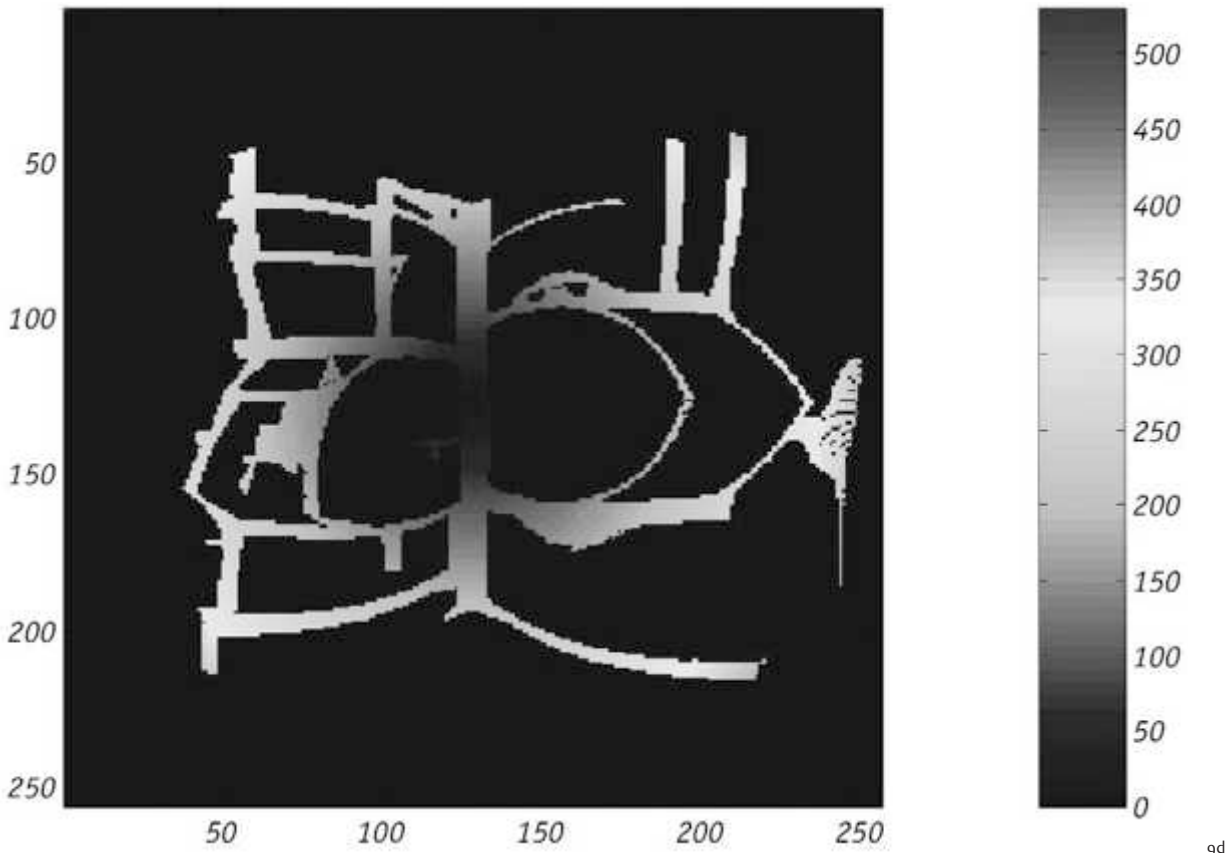
computed). From left to right, top to bottom: average, maximum, minimum by adding values in two opposite directions, minimum, maximum by adding values in two opposite directions,

average inside the buildings
 b Polar deformation on the London case study DEM from point [220,110] in image co-ordinates; deformation of 14, 35 and 70 pixels respectively; the polar deformation is

used to compute all visible points from the centre of the deformation
 c London case study: shadow volume in grayscale (left) produced by a virtual light bulb placed at the point

[192,113] in image co-ordinates, height 187m. Right: shadowed (black) and illuminated (white) pixels, which constitute the viewshed
 d Chronogeographic transformation of a portion of the

central London case study: deformation of the map so that radial distance from the centre point is proportional to travelling time (concentric circles are reached simultaneously)



gd

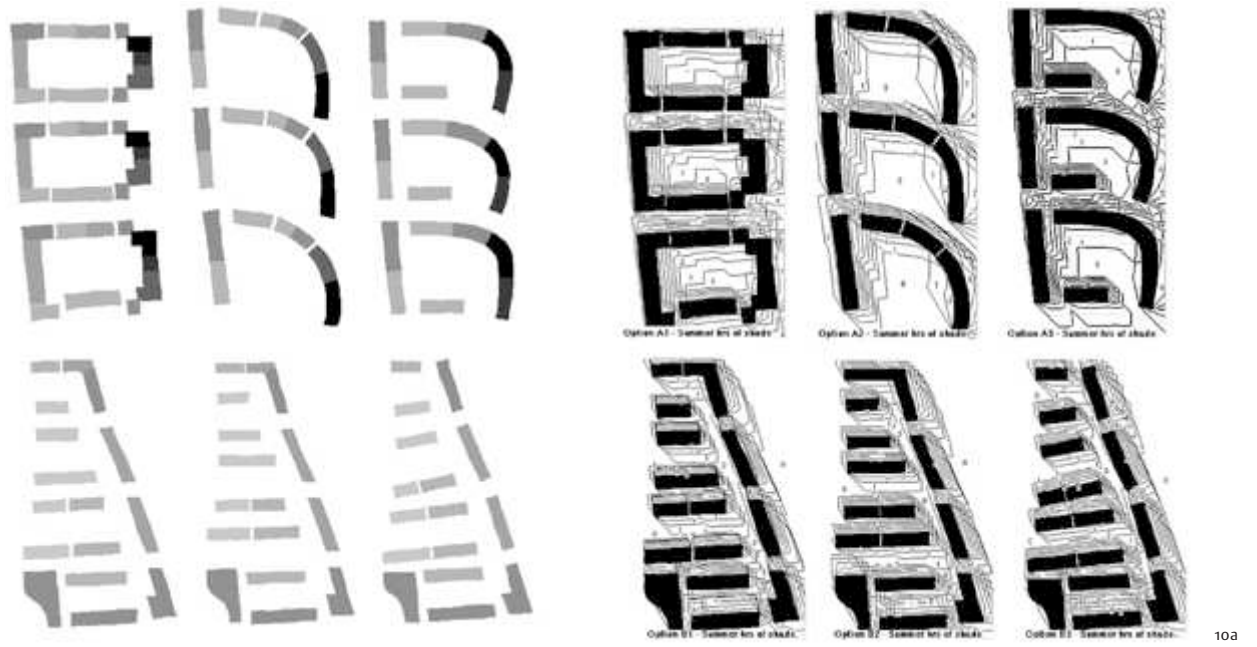
review two urban projects in which DEMs have been used. In general, different ways in which they can contribute to urban design can be distinguished:

- At a basic level, the analysis of DEMs adds to the knowledge of the designer. It helps in deciphering the built environment and provides relevant data on, say, the shadowing conditions of a given site. It informs, therefore, the making of massing hypotheses and can orientate the design at a preliminary stage. Analyses of this kind can and often are carried out on individual buildings. The use of DEMs allows them to be extended to the urban scale (where current software fails due to difficulties in modelling geometrical complexities) and to include new simulations, such as pollution dispersion analysis.
- Later in the design process, the analysis of DEMs can help practitioners choose between different alternatives. Design is often considered not as a one-off process, but as a circular one. In Simon's words (1969), it can be described '*as involving first the generation of alternatives and then testing of these alternatives against a whole array of requirements and constraints. There need not be merely a single generate-test circle, but there can be a whole nested series of such circles.*' The analysis of DEMs could then be used in simulation mode; it would help designers in the recursive optimization process and in making choices between different alternatives. It would receive as input different options, each of which would then be ranked in terms of the selected variable (say, energy consumption) – in a similar

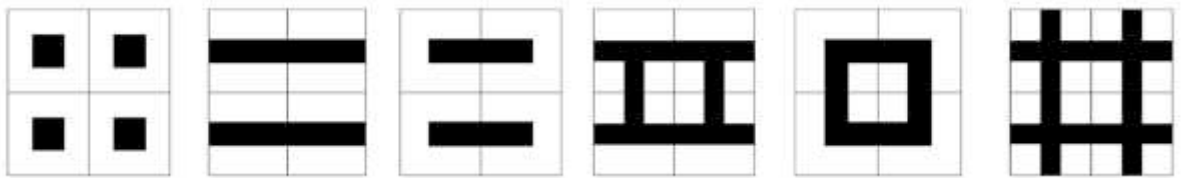
fashion to the way Space Syntax software is currently used in design exercises.

- At an even more ambitious level, the analysis of DEMs could evolve into a tool to stimulate invention. While the techniques described in the first and second points above could be defined as simply 'reactive', here a fully 'proactive' tool is discussed – ie, a tool which would not only test solutions, but suggest them. This would, of course, require some additions to the body of techniques that has been developed so far. They should be coupled, for instance, with the synthetic generation of DEMs or with combinatorial methods to produce designs. A similar approach was followed, among others, by the Hong Kong architect Michael Chan (2000) whose work, exhibited at the Venice Biennale 2000, is based on the automatic generation of building facades and their iterative selection based on the optimization of environmental criteria.

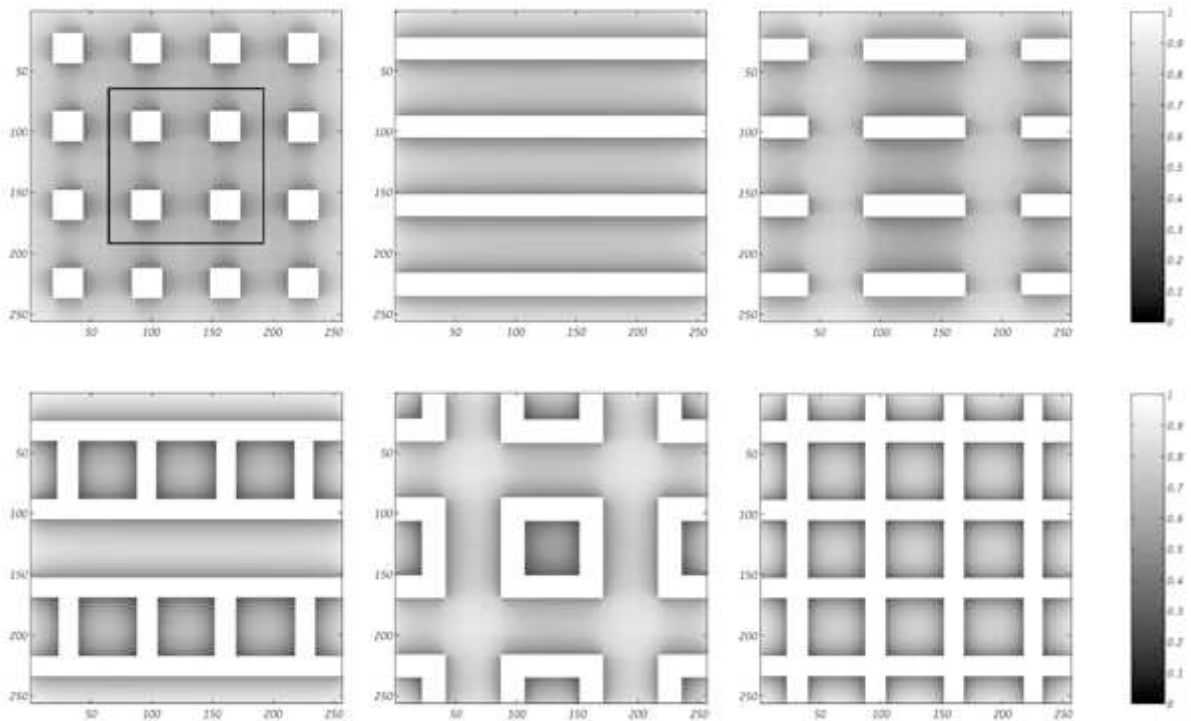
This section will briefly focus on the second point, showing how the analysis of DEMs can be used to compare different design options to inform architects and planners. The images in [10a], for instance, show the results of an analysis carried out for the Richard Rogers Partnership to compare a number of different schemes for the Greenwich Peninsula in terms of shadowing and accessibility to daylight. A sensible difference between the behaviour of the different options was detected, allowing the designers to make informed choices in the subsequent phases of design. Illustrations 10b



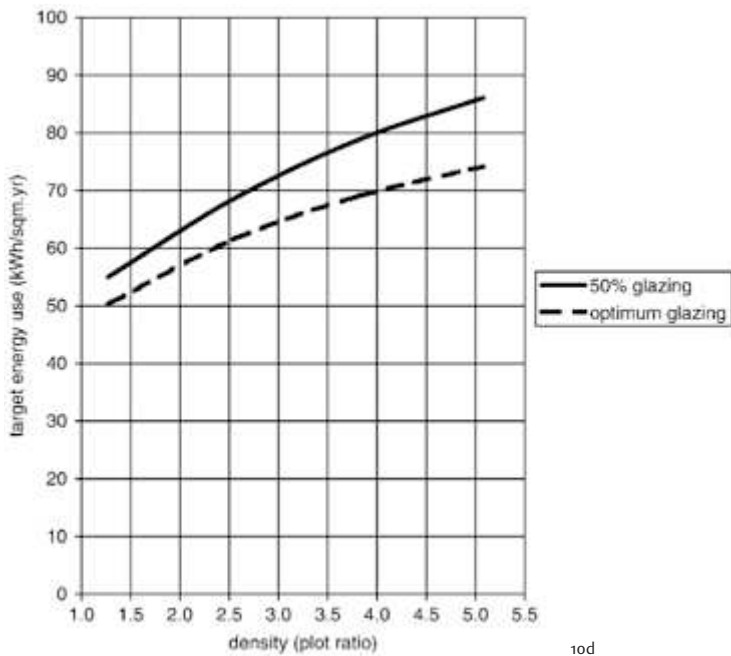
10a



10b



10c



10 The use of DEM to compare different design options
 a Development options in the Greenwich peninsula by Richard Rogers Partnership; the image on the right shows the number of hours of shadows during summer for different development options
 b Generic urban forms, based on Martin and March (1972) as modified by Steemers et al

(1997). From left to right: pavilions, slabs, terraces, terrace-courts, pavilion-courts and courts
 c Sky view factors at ground level for the generic urban forms shown in b
 d Effect of density on energy use for naturally ventilated offices in central London; this image was obtained with the LT analysis of DEMs as shown above

10d

and c address a more general planning problem, first discussed by Leslie Martin and others at the University of Cambridge during the late 1960s: what is the relative environmental performance of courtyards versus pavilions? A number of different configurations have been represented with DEMs, analyzed with image-processing techniques and later compared in terms of accessibility to daylight and sunlight at different times of the year. Finally, [10d] shows the simulated building energy consumption value in a portion of central London with changing built densities. It shows that a simulated process of densification – which in recent years has been often suggested in the UK as an effective way to reduce energy consumption in cities, mostly due to the reduction in transport costs – has its side effects: it results in reduced access to light and air and therefore in higher energy consumption in buildings and a generally poorer urban environmental quality.

Conclusions

Most current software to assist design focuses either on individual buildings or large portions of cities. A lack of tools occurs at the urban block scale, possibly

because of the difficulties of handling complex geometry. These difficulties, as we have seen, can be overcome by the use of the DEM – a versatile support for storing, manipulating and analyzing the geometry of the city, allowing the fast computation of many parameters.

Some of these parameters are commonly used within the architectural community. Others are relatively new. In some cases, it has been the very nature of DEMs that suggested analyses that had rarely been used in urban studies before. These include, among others, the estimation of building energy consumption using the LT Model and the computation of the sky view factor.

This growing amount of data that can be obtained from DEMs is naturally leading to the idea of an ‘urban infoscape’: a layered information system that could successfully inform urban design and planning. This seems, today more than ever, a necessity: only a greater power of simulation can satisfy the rapidly changing needs of contemporary design at the city scale. Today, as the leading architect and urbanist Rem Koolhaas (2000) puts it;

‘no longer is the city visualised or composed as much as it is empirically computed’.

Notes

1. However powerful, NIH Image has some speed and accuracy limitations. Matlab, a commercial software package with an extensive image-processing library, has also been used for some of the analyses presented in this paper.

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arq gratefully acknowledges:
 Nolli, 1
 Koen Steemers et al, 2a, 10b and d
 Authors, 2b, 5a-c, 6a-e, 7a-d, 8a-e, 9a-d, 10a and c
 G. A. Baxes, 3 (adapted), 4

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Biographies

Carlo Ratti is a practising architect who directs the newly established *SENSEable City Laboratory* at the Massachusetts Institute of Technology. He previously completed a PhD at the Martin Centre for Architectural and Urban Studies (University of Cambridge Department of Architecture), where most of the techniques presented in this paper have been developed. He is a Junior Fellow of the Aspen Institute and a regular contributor of articles on architecture to *Domus* and the leading Italian newspapers *La Stampa* and *Il Sole 24 Ore (Domenica)*.

Nick Baker trained as a physicist and has spent most of his career in building science. Apart from urban climate models, his other areas of interest include daylighting design, energy modelling and thermal comfort. He has published widely on all of these topics, including a recent book *Daylighting Design of Buildings* (with Koen Steemers, James & James, 2001). He has recently retired from full-time teaching at the Martin Centre for Architectural and Urban Studies, University of Cambridge Department of Architecture.

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