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Energy consumption and urban texture

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Abstract

This paper explores the effects of urban texture on building energy consumption. It is based on the analysis of digital elevation models (DEMs)—raster models of cities which have proven to be very effective in the urban context. Different algorithms are proposed and discussed, including the calculation of the urban surface-to-volume ratio and the identification of all building areas that are within 6 m from a façade (passive areas). An established computer model to calculate energy consumption in buildings, the LT model, is coupled with the analysis of DEMs, providing energy simulations over extensive urban areas. Results for the three case study cities of London, Toulouse and Berlin are presented and discussed.

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1. Introduction

“We are all passengers on Spaceship Earth”. Although Buckminster Fuller’s\textsuperscript{[1]} premonitory vision of the finiteness of global resources dates back to his notes from the late 1920s, it was only in 1973, with soaring oil prices, that energy conservation strategies burst onto the environmental agenda. As a result, the quantity of research in the field increased considerably: this was noted for instance by Farmer\textsuperscript{[2]}, whose bibliography of European and American literature on energy management and technology, limited to the building sector, reviewed over 700 titles.

Additional pressure to study energy conservation has increased in recent years due to general concern on climate modifications. It is now widely accepted that the combustion of fossil fuels with the consequent emission of greenhouse gases in the atmosphere is modifying long established climate patterns. As noted by the Intergovernmental Panel on Climate Change\textsuperscript{[3]} “the balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate”.

No part of the economic community can escape the urgency of reducing energy demands, but the building sector is particularly under pressure: approximately one half of the world’s energy resources are employed to control internal environments. UK data show that the energy requirements for buildings in the domestic and non-domestic sector exceed those for transport and industrial processes (see\textsuperscript{[4,5]}).

The first step in improving the energy performance of buildings is to study and simulate their behaviour. Many energy models and techniques have been developed for this purpose in recent years. However, these models usually adopt the perspective of the building designer: they tend to consider buildings as self-defined entities, neglecting the importance of phenomena that occur at the urban scale. In particular, the effect of urban geometry on energy consumption still remains understudied and controversial.

One reason for this lack is the difficulty of modelling complex urban geometry. Even simple algorithm for shadow casting, which are now included in most software packages such as AutoCAD (Autodesk, 2004), work at the scale of the...
building but fail on larger areas because of too much vectorial complexity. This paper aims to test the possibility of using a very simple raster model: the so-called digital elevation model (DEM), which is shown in Fig. 1. The DEM is a compact way of storing urban 3D information using a 2D matrix of elevation values; each pixel represents building height and can be displayed in shades of grey as a digital image. The analysis of DEMs with image processing techniques has already proven to be an affective way of storing and handling urban 3D information, and being very conducive to a number of urban analyses [6,21–23]. Could it be used to explore the effects of urban texture on building energy consumption?

All algorithms presented in this paper have been written using the Matlab software (2004), a well-known package for doing numerical computations with matrices and vectors. Matlab’s extensive matrix capabilities are supplemented by different toolboxes, among which is the ‘image processing toolbox’, with elaborate graphics outputs.

2. Context

Building energy performance is currently understood as dependent upon (see Fig. 2):

(1) urban geometry,
(2) building design,
(3) systems efficiency,
(4) occupant behaviour.

It should be noted that these four points are under the control of different actors in the building sector: urban planners and designers in (1), architects in (2), system engineers in (3) and occupants in (4).

According to Baker and Steemers [4] building design accounts for a $2.5 \times$ variation in energy consumption, systems efficiency for a $2 \times$ variation and occupant behaviour for a $2 \times$ variation. The cumulative effect of these factors can lead to a total variance of 10-fold. In practice, variance in energy consumption of buildings with similar functions can be as high as 20-fold. Is urban geometry the $2 \times$ factor missing?

Urban geometry (point 1) mainly relates to the availability of sunlight and daylight on building façades: highly-obstructed urban areas are deprived of useful daylight and solar gains, thus necessitating generally higher energy inputs. There are also indirect effects, as urban geometry affects urban microclimate. As noted by Givoni [7]: “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”. These changes in the urban environment result in modified energy consumption. Also, air pollution and noise are dependent on urban form, thus affecting the potential for natural ventilation via a behavioural mechanism.

Despite the evident relationship between urban geometry and energy consumption, this link is generally neglected, possibly because of the complexity of the environmental processes involved. Most software for building simulation tends to concentrate on (2) and (3), i.e. at the level of architectural and systems design, while neglecting (1). For instance, Howard et al. [8], in their guidance on selecting energy programs, reviewed 33 software packages, just 10 of which take into account the influence of overshadowing in urban areas.

Even software developed to simulate energy consumption at the city scale tends to neglect the effects of urban...
geometry. In most of the cases this software has diagnostic aims (i.e., the evaluation of energy consumption over extensive areas) and assumes default values to simulate the effects of urban geometry. This is the case, for instance, for the energy and environmental prediction (EEP) model, developed at the Welsh School of Architecture in Cardiff (cf. [20]). EEP uses a Geographic Information System platform linked to a number of sub-models to account for the energy and emissions produced by buildings, transport systems and industry. The component to evaluate domestic energy use is based on a BREDEM type calculation [9], which does not take into account urban geometry and overshadowing of buildings. A similar approach, also based on BREDEM, is adopted by the solar energy planning (SEP) tool, a GIS-based program to support urban planners and designers in evaluating the potential for solar heating [10].

Nevertheless, the quantitative contribution of urban form to energy consumption can be important. The impact of overshadowing on buildings alone can be quite strong. For example, Fig. 3, from Baker and Ratti [11], shows the effect of the mean elevation of the skyline from a building façade (urban horizon angle, UHA) on the annual energy use for heating, cooling and lighting for an office building in the UK. Quite complex processes are occurring; in winter the south façade is deprived of useful solar gains thus increasing the heating load, whereas the north façade is unaffected since the solar gains are insignificant. For summer cooling energy the benefit is reversed, but much weaker. Both orientations show a marked increase in lighting energy demand, a fact probably recognised (but largely forgotten) as evidenced by various ‘rights of light’ planning laws. What is interesting is that, all other parameters being equal, urban geometry in the neighbourhood of a given building has quite a large impact.

The estimate of the effects of urban texture on energy consumption is the focus of this article. With an approach that is the opposite of the building scientist’s, default values will be attributed to all variables except those that relate to the description of urban form. This would mean considering mainly parameters in points (1) and (2) above, such as the surface-to-volume of urban texture, the amount of naturally-lit (or passive) zones, the self-shading of urban texture, etc.

The study is a morphological one, where only the parameters related to urban form will be taken into account. It does not have a fully diagnostic aim, i.e., to provide exact energy consumption figures at the urban level, but rather comparative figures. In this sense, it is similar to research on urban forms that was started in the 1960s at the Centre for Land Use and Built Form Studies at the University of Cambridge. In a short mathematical divertissement March [12] asked himself the following question: what shape should a building be to reduce heat losses? His assumptions and results, which suggested the advantage of compact shapes and had a considerable influence at the time in promoting deep plan underglazed buildings, are reviewed below.

March’s study led to subsequent work in the 1970s. Owens [13] reports on a study by BRE where heating requirements of hypothetical dwellings of similar volume and insulation standards but different form were compared. Results were obtained for detached, semi-detached and terrace houses, as well as for intermediate and top flats, showing a 1–3 variation in figures.

More recently, the focus on CO₂ production has shifted attention away from heating energy (which has become less due to higher standards of insulation and greater internal gains) to other electrical uses such as lighting and mechanical ventilation. The influence of geometry on these is different, indeed almost reversed, from that on heat losses. Consequently, more recent classifications of built form for energy analysis, such as that of Steadman et al. [14], developed within the non-domestic building stock (NDBS) database for the Department of Environment (UK), reject the elementary surface-to-volume ratio in favour of other building envelope parameters. But before examining this in more detail, March’s approach is described.

3. What shape should a building be to reduce heat losses?

This section reviews March’s approach [12] to the analysis of heat losses as a function of built form: a model of a building which takes into account just the necessary parameters for the study. In the March case, the built form is a perfect rectangular parallelepiped, each surface of which is made of a homogeneous material with a given transmittance value; all other features are considered not relevant or negligible compared to this.

Furthermore, some assumption on the physics of the process should be made. In the first approximation it can be assumed that heat loss is proportional to the thermal transmittance and surface area of each face of the built form; and that no heat transfer occurs from the building to the ground.
Under these conditions, March [12] proves that for a rectangular parallelepiped building, whose exposed surfaces have equal transmittance and whose floor conducts no heat, the shape that minimises heat losses is half a cube.

Beyond March’s analysis, if ground losses were taken into account, and were presumed equal to losses through all other sides of the building, the optimum shape would become a cube (this fact can be proven again with simple mathematics or with considerations on symmetry). Furthermore, if constraints on the shape to be a perfect rectangular parallelepiped were released, a sphere would be obtained, which encloses the maximum volume within the minimum surface.

### 4. Deriving built volume and built surface on a DEM

An approach similar to March’s could be applied over extensive urban areas. If the thermal transmittance of buildings is considered uniform and if no heat loss exists to the ground, the total heat losses can be estimated with the surface-to-volume ratio. This can be calculated on a DEM as shown below.

#### 4.1. Built volume

The volume built on each pixel is an elementary prism whose base is a unit square and whose height is its value on the DEM. These values in image co-ordinates then need to be converted into real values (for instance, m), by multiplying them by the ground area of each pixel and the scale of heights.

The total built volume on a DEM comes straightforward therefore by adding the elementary volumes on each pixel, an operation that can be performed by the function SUM in Matlab.

#### 4.2. Built surface

It will be assumed, as a first approximation, that the city is composed only of vertical (façade) and horizontal (street and roof) surfaces. The computation of horizontal surface is straightforward, as it is equivalent to counting the number of roof pixels and multiplying it by the unit surface of each pixel.

Vertical wall area proves to be more challenging. Image processing software packages, such as Matlab, have commands to extract perimeter pixels from images, which seems a good start. However, summing pixels and multiplying by the scale does not necessarily give the right answer. Walls aligned to the axes measure correctly, but walls at 45° account for less than they should, being reduced by a factor 1/√2.

A more precise answer requires a different approach. An image can be interpreted as a 2D function:

\[ f = f(x, y) \]

The vector normal to this surface on each point can be written as

\[ \hat{n} = -\frac{df}{dx} \hat{i} - \frac{df}{dy} \hat{j} + \hat{k} \]

By normalising this vector, the unit normal vector is obtained

\[ \hat{n} = \frac{\hat{n}}{|\hat{n}|} = \frac{-\left(\frac{df}{dx}\right) \hat{j} - \left(\frac{df}{dy}\right) \hat{i} + \hat{k}}{\sqrt{\left(\frac{df}{dx}\right)^2 + \left(\frac{df}{dy}\right)^2 + 1}} \]

Now consider an area \( A_{\text{ground}} \) on the ground, say a unit pixel. This area \( A_{\text{ground}} \) can be projected on the surface \( f(x, y) \) using the dot product between the unit vector normal to the surface and the unit vertical vector, according to the following formula:

\[ A_{\text{ground}} = A_{\text{topsurface}}(\hat{n} \cdot \hat{k}) \]

which gives

\[ A_{\text{topsurface}} = \frac{A_{\text{ground}}}{(\hat{n} \cdot \hat{k})} \]

or, by substituting

\[ A_{\text{topsurface}} = A_{\text{ground}} \sqrt{\left(\frac{df}{dx}\right)^2 + \left(\frac{df}{dy}\right)^2 + 1} \]

This formula defines the relationship between pixels on the ground and areas on façades. \( x \) and \( y \) derivatives on a DEM can be obtained by filtering the image using Sobel edge detectors\(^1\) (see for instance [16]). The Sobel filter produces null results on the horizontal parts of the DEM, except in correspondence of façades. Two images are produced, with \( x \) and \( y \) results; then they are squared, summed and reduced to the square root. Finally, by counting the number of non-zero façade pixels and by multiplying the result by the unit ground surface of each pixel (standard operations in Matlab), the total vertical surface area is obtained.

#### 4.3. Surface-to-volume ratios of London, Berlin, Toulouse

Using the procedure described above, data on built surface and volume were collected in three DEMs that represent central areas in London, Toulouse and Berlin (Figs. 4 and 5). Berlin has the minimum surface-to-volume ratio and therefore minimises heat losses; London and Toulouse follow. The increase can be as large as 45%, a figure that suggests a potentially significant energy impact.

However, a question arises: is it correct to aim to minimise the exposed surface of buildings? If this principle were accepted, the best shape to accommodate all the volume of the London case study site would be a March half-cube (or a full cube if ground losses are taken into account), such as that presented in Fig. 6.

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\(^1\) It should be noted that the Sobel filter approximates vertical surfaces with slightly sloped façades.
Apart from any consideration on its architectural quality, such a shape, while theoretically minimising heat losses, is unlikely to minimise energy consumption as a whole. In fact, heat losses just tell part of the story of energy consumption in buildings, as explained below.

5. The passive zone concept

The surface-to-volume ratio is an interesting descriptor of urban texture. It defines the amount of exposed building envelope per unit volume, and can be used in a number of different applications (possibly, estimating the quantity of façade-paint necessary per unit built urban fabric). Its relevance to the energy consumption of buildings, however, must be considered carefully. Minimising heat losses during the winter requires minimisation of the surface-to-volume ratio; but this implies a reduction of the building envelope exposed to the outside environment, thus reducing the availability of daylight and sunlight and increasing energy consumption for artificial lighting, natural ventilation, etc.

In fact, the LT method [4] suggests that the main energy distinction to be drawn within buildings is a function of the exposure to the outside environment. This concept is made explicit with the definition of passive and non-passive zones, which quantify the potential of each part of a building to use daylight, sunlight and natural ventilation. By a simple rule of thumb, based on empirical observations, all perimeter parts of buildings lying within 6 m of the façade, or twice the ceiling height, are classified passive, while all the other zones are considered non-passive (Fig. 7).

Also, Steadman et al. [14] adopt the concept of passive and non-passive space as one of the two key criteria in the energy classification of built forms. By analysing statistics from a number of purpose-built office buildings in Swindon, they detected a bi-modal distribution of plan depths. One
group of buildings is 14 m in depth and has the potential of being naturally lit and ventilated, while the other is in the range 18–22 m deep and is likely to require air-conditioning—and therefore higher energy inputs.

The proportion of passive to non-passive areas in buildings provides an estimate of the potential to implement passive and low energy techniques. It should be noted, however, that this is only a potential: the perimeter zones of buildings can still be wastefully air-conditioned or artificially lit. In some cases, passive zones can consume more energy than non-passive zones, especially when excessive glazing ratios and untreated façades make them particularly vulnerable to overheating during the summer and to heat losses during the winter.

Below it will be shown how to derive the ratio of passive to non-passive areas on a DEM.

6. Detecting passive and non-passive zones on a DEM

Passive and non-passive zones are defined on a floor-by-floor basis. A slicing procedure has to be adopted to convert the 3D DEM into planar information. This process of slicing the city at different levels can be easily performed with a simple image processing operation based on subtraction. Fig. 8 shows the London DEM sliced on the fifth floor (15 m).

Having sliced the DEM, the problem from an image processing viewpoint can be stated as follows: given an image consisting of black (built) and white (unbuilt) pixels, assign to each black pixel a value corresponding to its distance from the nearest white pixel. The solution to this problem can be obtained using algorithms developed for distance transformations in digital images (for a review, see [17]).

The application of the Euclidean distance algorithm, which tells for each internal pixel its Euclidean distance from the closest boundary, is shown in Fig. 9. Passive zones at a certain height can easily be detected by the Euclidean distance transformation with a thresholding operation. This operation is based on detecting all pixels within a certain range—for instance $0 < d < d_{\text{max}}$, where $d_{\text{max}}$ is the value in pixels that corresponds to a 6 m
distance. Non-passive zones, where the distance is greater than 6 m, $d < 6$, can subsequently be detected by subtraction. Results for London, Toulouse and Berlin are shown in Figs. 10 and 11.

The integration of results on a floor-by-floor basis allows the identification of the total passive and non-passive areas on the DEM (Fig. 12). Figures rank the cities in the order Toulouse, London and Berlin, which is reversed, if compared with the surface-to-volume parameters. This is not surprising: in the case of buildings with a considerable grain size and in any case a distance between opposite facades greater than $6 + 6 = 12$ m, the passive to non-passive ratio is also an approximate indicator of the building surface-to-volume ratio (in the case of buildings with infinite grain size, the two ratios would be the same).

However, two conflicting exigencies for energy conservation appear: reducing the building envelope, which is beneficial to heat losses, and increasing it, which is favourable to the availability of daylight and natural ventilation. Which of the two phenomena prevails in the global budget of buildings?

The above question is not likely to have an absolute answer. At very high latitudes, where solar gains are scarce and temperatures harsh all year long, heat conservation strategies might well be prevalent over the collection of daylight and natural ventilation. Which of the two phenomena prevails in the global budget of buildings?

More generally, the relative importance of the two phenomena (losing heat and receiving beneficial gains through the façades) will be climate-dependent and differ between, say, London and Rome. For a given climate, it can only be assessed by a comprehensive analysis, which takes into account all the energy processes that happen in buildings. A building is an integrated entity: structurally, functionally and environmentally. Heating, lighting, ventilating and cooling should be considered simultaneously in assessing energy consumption. This will be presented in the following section, which aims to couple image processing techniques with the LT method (Fig. 13).

7. An integrated approach: the LT model

7.1. Brief description of the LT model

The LT model (where LT stands for lighting and thermal) was developed as an energy calculation tool within the now widely known LT method [15,4]. The LT method was initially developed as a spreadsheet method that allows the prediction of energy consumption in non-domestic buildings at the concept design stage. It was developed to help designers to determine how the energy consumption of a building might relate to the early architectural parameters. Therefore, in the LT method, most parameters are initially given default values.\(^2\)

The LT model is the integrated energy model used to generate the data for the LT method. It predicts the annual heating, lighting, ventilating and cooling energy use/m\(^2\), based on the simulation of a 9 m x 6 m x 3 m module with one exposed glazed wall, as shown in Fig. 14. Previously spreadsheet based [18], the model has recently been recoded in the form of a stand-alone computer model.

The energy flows considered are depicted in Fig. 14. First, the model evaluates the heat conduction through the external envelope, and ventilation heat loss (or gain): using monthly mean temperatures, defined in a climate file, and an average internal temperature, a monthly gross heating load is then calculated. Results are scaled using correction factors, which account for the number of occupied days within a given month and intermittent daily heating profiles. A similar procedure, although using a different reference internal temperature, is used to calculate cooling loads.

The model then evaluates daily solar gains, as the sum of sky irradiation (direct and diffuse), and diffuse irradiation from ground and walls. An hourly shading coefficient calculation accounts for shading due to adjacent buildings. Furthermore, if there is a cooling load blinds are

\(^2\) Energy use is strongly dependent on engineering parameters such as illuminance level, boiler efficiency and $U$-values. In the LT model default values are suggested, but the user is invited to change or select these to suit the function and context of the building.
automatically employed to reduce/omit direct gain to mimic good occupant behaviour and adaptive opportunity. Finally, a solar utilisation factor is applied, as not all of the solar gains available are useful in offsetting auxiliary heating.

At the same time available daylight is estimated. Two reference points, within the front and rear halves of the LT module, are defined. The daylight calculation is based on the Hopkinson et al. [19] equation with the addition of the concept of urban horizon angle (UHA), the altitude angle subtended from the mid-point of the module window to the mean roof height of the adjacent buildings. This angle is then projected back into the module to derive sky and obstruction view factors for each reference point and subsequently estimate daylight received from the sky.

Daylight reflected from opposite façades is then added to this value. This requires an estimation of the amount of light falling on the opposite façades. With the same principle of UHA, the obstruction sky view (OSV) angle is defined in order to quantify the luminance of the obstructing façades (as a function of their view of the sky). Finally, the total internal illuminance is determined. If this is below the design illuminance level then artificial lighting is switched on; this gives a monthly electrical consumption for artificial lighting and a monthly heat gain.

The lighting heat gains and useful solar gains, together with casual gains from occupants and equipment, are then subtracted from the gross heating load to establish the net heating load. If the gains are more than the gross heating load, then the net load is zero or a cooling load. The cooling load starts when the gains are sufficient to raise the average temperature above the cooling reference point; it is added on to the energy demand for fan and pump power.

Finally, heating and cooling loads are translated into delivered energy using either a boiler efficiency or a cooling coefficient of performance. The monthly energy consumption is calculated for a cell and then translated into values/ m². This is then totalled for the whole year, and corrected with factors to reduce all energy to primary energy, i.e. the energy value of fuel at source. These factors account for distribution and power station thermodynamic efficiency losses, allowing the different fuel inputs for lighting, heating and cooling to be reduced to one common unit. In doing this, a number of simplifying hypotheses are necessary, as discussed by Baker and Steemers [4].

7.2. Urban parameters in LT

The LT model described above seemed well suited to simulate energy consumption at the urban scale, as it captures the principal energy flows of buildings with reasonable accuracy without necessitating the computational demands of full dynamic simulation. Nevertheless, the LT model requires numerous inputs to perform energy consumption calculations. Over 30 parameters are necessary, including building U-values, interior and exterior reflectances, illuminance data, heating efficiency and setpoint, etc. A full listing and explanation can be found in [4].

In the LT method, however, most of these parameters are assigned default values and only those related to design are left open for users to define. In a similar way, since the aim in this study is to highlight the effects of urban form upon building energy consumption, default values are assigned to
all variables, except those that relate to urban geometry. These are:

(1) distance from the façade (passive/non-passive condition);
(2) orientation of the façade;
(3) urban horizon angle (UHA);
(4) obstruction sky view (OSV).

All other parameters have been given default values, which were provided by the developers of the LT model and have been set at values that simulate the energy consumption of a standard office building. All buildings in the London, Toulouse and Berlin case studies have been considered as non-domestic. As for the glazing ratio of façades, which is one of the variables of the LT method, it is fixed for the moment at a value of 50%.

A final question needs mentioning here: should energy consumption simulations in London, Toulouse and Berlin be based on different climatic data files? The interest being not in the derivation of absolute figures, but in exploring the dependence of energy consumption on urban texture, it was decided that the effects of climate should be standardised to that of London. Therefore the results presented should be interpreted as figures for fictitious versions of Toulouse and Berlin: cities of their geometries subjected to London’s climate.

8. Deriving the LT parameters on a DEM

Image processing of a DEM seems the best way to derive the parameters needed by the LT model on extensive urban areas. In fact, were it not for this analysis technique, this process would probably have been prohibitively costly.

The LT method being a floor-by-floor method, the DEM needs to be sliced at different heights, in order to convert the 3D information of the DEM into floor surfaces, as explained above. Three metre representative floor height has been adopted. Calculations are then performed on each pixel of the image, inside the buildings and on façades; pixels inside the buildings are assigned the values of orientation, UHA.
and OSV that are taken from the closest (in Euclidean terms) façade pixel.

For each pixel, LT needs the following input: whether the space is passive or non-passive, the façade orientation, the UHA and the OSV. The derivation of passive zones was presented above, while that of the other parameters follows.

8.1. Orientation of façades

Filters have been developed in image processing to detect edges. In particular, by filtering the DEM with a Sobel edge detector, it is possible to construct $f'_x$ and $f'_y$, x and y derivatives on a DEM. The orientation of the façade can then be derived as $\theta = \arctan(f'_y/f'_x)$. Because the standard Sobel filter works on a $3 \times 3$ kernel, it can scan only a limited number of configurations and values are approximated in classes of 22.5°. Results for the London, Toulouse and Berlin DEMs at a given height are presented in Figs. 15 and 16.

8.2. Determining the urban horizon angle (UHA)

As noted earlier the UHA is used by LT to determine the effects of overshadowing due to adjacent buildings. The LT model uses as a reference an urban canyon of uniform width $W$ and height of buildings $H$. Therefore, the computation of the UHA is straightforward: on a given façade it is the height $H$ of the opposite buildings divided by the canyon width $W$ ($H/W = \tan(UHA)$). However, with complex urban geometry, the computation of UHA is considerably more involved.

The algorithm used is a variation of that described by Ratti and Riches [6] for shadow casting. Therefore, on each façade the city was scanned in several directions. The value in the direction perpendicular to the façade was averaged with six other values, taken in the range $[0, 67.5° + 67.5°]$ at regularly spaced intervals of 22.5° (Figs. 16 and 17). Contributions from different directions, however, do not have the same impact: solar radiation falling incident on façades from low side-angles has a reduced effect,
proportional to the cosine of the angle between them and the normal to the façade. This is accounted for by weighting the different values that lead to the mean UHA (Fig. 18).

8.3. Determining the obstruction sky view (OSV)

Energy falling on a given façade (termed here ‘primary’ façade) comes both from the sky and from radiation reflected from opposite façades. In order to estimate the latter contribution, the LT model needs to know the amount of radiation that falls on the opposite façades through their angle of obstruction. This is called obstruction sky view (OSV) and is basically the same as the urban horizon angle (UHA) for the obstructing façades.

This is derived by the same procedure as the above UHA. On each primary façade an average OSV needs to be obtained: as above, seven directions in the range $[-67.5^\circ, 67.5^\circ]$ at regularly spaced intervals of $22.5^\circ$ are considered, weighted again with a cosine correction. The OSV in London, Toulouse and Berlin is shown in Fig. 19. Results are very similar to those for UHA (cf. Fig. 18).

9. Energy consumption figures and parametric studies

With the geometric parameters outlined above, it was possible to proceed with the energy modelling. Firstly, the geometric parameters were passed from Matlab to the LT model on a per-pixel basis. Then LT model results were produced and overlaid onto the DEM, resulting in a new image. Results for London, Toulouse and Berlin on the second floor (height 6 m) are shown in Fig. 20.

The LT calculation performed on a per-pixel basis can be time consuming, resulting in several minutes per slice (or floor). As an alternative, a 3D matrix $10 \times 10 \times 16$ of pre-computed values was generated using the LT model for the range of urban parameters being investigated. Values were finely tabulated: 10 increments of UHA and OSV for each of 16 orientations for passive zones and a non-passive zone. This reduces the computation time of the energy simulation to a few seconds per floor, without introducing any significant error.

On a floor-by-floor basis the results show the importance of the distinction between passive and non-passive zones. Parts of buildings within 6 m of a façade present a significant reduction in energy consumption (almost 50%) compared
with non-passive ones. This is true even for passive zones which face small and obstructed courtyards: while losing energy through the glazed façade, they still benefit from natural light and ventilation.

When results are integrated on all floors, the values of Fig. 21 are obtained. Energy consumption values summed over all heights are ranked in the order Toulouse, London and Berlin: 0.0668, 0.0683 and 0.0731, respectively. The order is reversed, compared with the surface-to-volume ratio, which means that heat losses through the building envelope are not the most prominent component of the total energy budget in buildings. On the contrary, the passive to non-passive area ratio seems a better indicator of energy consumption. This is true at least for the southern UK climate and for the three urban textures considered in this study.

The London, Toulouse and Berlin case studies which have been considered in this work present extremely varied grain sizes. At a first approximation, they are representative of a medieval, a Georgian and a modern city, and cover a wide range of urban textures. However, new patterns might emerge on different textures: only the repeated integrated analysis of energy consumption can tell which phenomena prevail. For instance, consider an imaginary urban texture where the grain size of buildings is $<12$ m, i.e. all the surfaces are passive. Then, any additional increase in building envelope would probably not ameliorate daylighting levels but simply increase heat losses.

The relative variation of energy consumption figures for London, Toulouse and Berlin is less impressive than, say, the variation of the surface-to-volume and passive to non-passive ratios. This result could be expected, as the LT analysis produces an integrating effect, which results in a lower sensitivity to urban morphology.

Nonetheless, almost a 10% difference is shown between the annual per-metre energy consumption in Toulouse and Berlin, simply due to the effects of urban morphology. A higher difference could be obtained by selectively changing LT parameters initially set as defaults. For instance, instead of a standard glazing ratio of 50% on all façades, an adaptive glazing ratio could be considered. This would be the optimum glazing ratio, i.e. the glazing ratio that corresponds to the minimum energy consumption. It can be identified on each pixel by running the LT simulation with different glazing ratios (for instance 10 times with increases of 10% each time) and by selecting the minimum.

The interest of this work would not only be amplifying the differences between urban textures, but also understanding which would be the best glazing ratio strategies on a given site. For instance, glazing ratios could be increased in built-up

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3 It should be noted, however, that this is not a real option, especially in contemporary cities where deep-plan buildings are the major driving force.
areas where availability of daylight is scarce and decreased in unobstructed areas where there is an overheating risk.

Energy consumption in London, Toulouse and Berlin for optimum glazing ratio values is shown in Fig. 22 for the second floor. The difference from the previous values is shown in Fig. 23. It is interesting to analyse the value of the optimum glazing ratio, presented in Fig. 24. Variations occur between approximately 20 and 55%, the latter corresponding to highly-obstructed areas.

Integrated total energy consumption figures for London, Berlin and Toulouse in passive zones are reduced by a constant fraction (approximately 6–7%) when optimum glazing ratios are considered. This reduction of energy consumption in passive zones will propagate itself on the

Fig. 23. Difference of Figs. 20 and 22 energy saving due to the optimisation of the glazing ratio in London, Toulouse and Berlin on the second floor (height $h = 6$ m); energy consumption decreases, especially in small courtyards and obstructed areas; values in kWh m$^{-2}$ year$^{-1}$.

Fig. 24. Value of the optimum glazing ratio, which minimises energy consumption, in London, Toulouse and Berlin on the second floor (height $h = 6$ m); small courtyards and obstructed areas can reach glazing ratios as high as 50%, while less obstructed areas rarely exceeds 30%; the variation does not appear to be orientation sensitive, as shown in Fig. 25; values in %.

Fig. 25. Variation of the optimum glazing ratio with orientation, averaged over all heights; results for London, Toulouse and Berlin.
total energy consumption by accentuating the difference, due to different passive to non-passive ratios.

Finally, what is the spatial variation of the optimum glazing ratios? Fig. 25 shows the average on all heights for each orientation. While a slight decrease in the ratio can be observed in the southern directions, it does not seem very sensitive to orientation. This is due to the fact that south-facing façades receive solar gain during cold seasons, but require more energy for cooling during the summer, resulting in a compensating effect. In fact, the difference between orientations would be more evident if only heating and lighting were considered in the LT simulation.

Fig. 26 is more interesting, showing the variation with height of the optimum glazing ratio. Highly overshadowed façades (for instance on the lower floors) require higher glazing ratios. Glazing ratios decrease with height, with a pattern that repeats itself in all cities. Optimised values such as these could eventually become recommended values in local design guidelines.

10. Conclusions

This article opened with a question: could the analysis of DEMs be used to explore the effects of urban texture on building energy consumption? The answer is in the affirmative. The analysis carried out in this article proved that the DEM is an effective support to derive morphological urban parameters quickly. Some of these were then passed to a simulation tool (LT), in order to get energy consumption figures.

A number of results also emerged on the relationship between city texture and energy consumption. The research proves that the surface-to-volume ratio, while being an interesting morphological parameter, does not describe the total energy consumption in urban areas. A better indicator seems to be the ratio of passive to non-passive zones, although accurate energy consumption values can only be derived from an integrated simulation such as LT. Although the results presented might seem predictable to a building physicist, they do not seem to have been proved so far at the urban scale.

The results of the LT simulation show an integrating and smoothing effect, so that the sensitivity of energy consumption on urban geometry is relatively small, especially when compared with the impact that can be attributed to systems efficiency or occupant behaviour? Probably not. First, a 10% variation is still a respectable value. Values of this order of magnitude could have a tremendous impact on the energy budget of cities and would justify careful thought in urban planning. Second, the current study has considered only three cities: London, Berlin and Toulouse. More parametric studies might increase the variation in results. Changing the climatic data in the LT method might also result in an amplification of the range of results. This would probably be particularly true in southern European locations, where the relative importance of exposure of the building envelope versus the danger of heat losses is greater.

Finally, referring back to the diagram in Fig. 2, this study assumed that the various factors affecting energy consumption were independent: in other words, that there was no influence between urban context, building design, efficiency of building systems and occupant behaviour. Urban geometry was selected as the only variable of interest and its impact on energy consumption was quantified with all other parameters being equal. In reality, this is an approximation. The problem is a multi-variable one, where interactions of various kinds occur. For instance, it could be claimed that an occupant is more likely to adopt energy-friendly behaviour if he lives in an energy efficient house, or that an architect is more eager to adopt bioclimatic strategies if his site falls within an urban development that was environmentally conceived (to minimise overshadowing, maximise wind penetration, etc.). If these mechanisms are true, a substantial amplification of the consequences of urban geometry on energy consumption could be expected. As in a cascade process, the effects of choices would propagate from one level to the next. And being at the top of the scale, urban design could theoretically have the most impact, influencing building design, the efficiency of building systems and occupant behaviour. But quantifying this influence lies outside the scope of the present study.

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References