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Passive solar urban design: ensuring the penetration of solar energy into the city

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Abstract

Site layout has a big impact on the viability of passive solar heating in buildings, as tall obstructions can block low winter sun. This paper reviews a range of tools to predict solar access in obstructed situations. They range from simple angular criteria, through sunpath diagrams and solar gain indicators to computer programs. The paper then examines criteria and techniques that can be used to evaluate solar access in dense urban layouts. Ways to protect solar access to existing buildings are also examined. Many of the techniques currently available are less suited to urban areas at high latitude. The paper suggests alternative approaches. © 1998 The Building Research Establishment. Published by Elsevier Science Ltd. All rights reserved.

1. Introduction

Passive solar design involves arranging the form, fabric and systems of a building to increase the benefits of ambient energy for heating, lighting and ventilation, to reduce the consumption of conventional fuels. It represents a flexible and attractive way to use renewable energy in buildings. Significant energy savings can be achieved. Yannas [35] quotes UK housing case studies saving over 50% in space heating energy requirements compared with the then standard design practice. Passive solar buildings can also have enhanced amenity value; occupants enjoy contact with the outside, with access to natural light and fresh air. In many cases passive solar design can be achieved with little or no extra cost compared to an equivalent conventional building [35].

Site layout is a key factor affecting the viability of a passive solar building. Tall obstructions can block incoming light and solar heat. They can also reduce the viability of passive cooling by reducing ventilation flows and trapping localised pollution. This area is currently the subject of a three year project "POLIS: Urban planning research actions to improve solar access, passive cooling and microclimate" [22]. The project is jointly funded by the European Commission's JOULE research programme, and

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by national funding agencies including the UK Department of the Environment's Energy Related Environmental Issues (EnREI) programme. The aim of the work is to enable designers to produce comfortable, energy efficient buildings surrounded by pleasant outdoor spaces, within an urban context that itself aims to minimise energy consumption and the effects of pollution.

Passive design covers a range of issues including the provision of daylight [7] and passive cooling [31]. However site layout has the biggest impact on passive solar heating. Figure 1 shows why. It shows the area of the sun's motion visible from a south facing wall. With a 10° obstruction opposite (lower dashed line), sunlight is received nearly all winter. But with a 40° obstruction (upper dotted line) all the winter sun is blocked. The benefits of solar heat gain are lost, but the overheating risk, due to unwanted solar gain in summer, still remains.

NBA Tectonics [26] have carried out a project to quantify the energy impact of site layout on passive solar housing. They used low and medium density UK housing estates as case studies. Figure 2 shows an example. Passive solar design can save 11% of the space heating in a typical dwelling; but these savings were reduced to less than half with non-ideal site layout.

Previous studies on passive solar design have concentrated on the use of "green field" rural or suburban sites. These are now increasingly scarce. To make a major impact in the future, passive solar has to move into the city. Environmental awareness extends to land use as well as low energy and resource consumption. Solar design

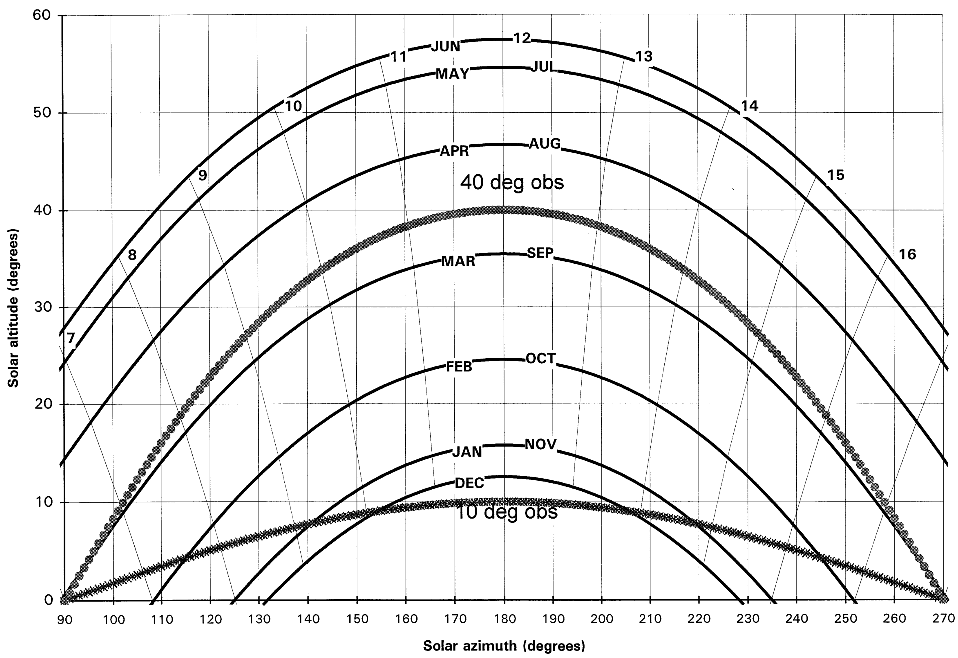

Fig. 1. Sunpath diagram: latitude 55 degrees, showing impact of obstructions.

needs to come to terms with this issue, making the most of obstructed urban sites rather than using up scarce open land.

This paper reviews current techniques to quantify solar access and examines how far they can be applied within the urban context. Potential constraints can include:

- large obstructions;
- uneven obstructions of various shapes;
- non-optimal glazing orientation;
- self obstruction by the building itself (for example by extensions or within courtyards).

Often new development may restrict solar gain to existing buildings nearby. This is an important issue to architects, planners and building owners, but is almost never mentioned in existing design handbooks. Quantitative guidance is therefore needed on safeguarding existing buildings, in particular the special needs of buildings which rely on solar energy. As the uptake of solar technologies increases, this is likely to be increasingly important.

Section 2 of the paper reviews potential analysis tools which can be used to evaluate solar access. These range from simple angular measurements to the use of computer programs to evaluate solar heat gain. Both the prediction methods and the criteria they use (or imply) are examined together. A solar use criterion is useless unless a layout can be shown to comply. Conversely a prediction method is of little value unless there is some sort of yardstick to identify good or bad performance.

2. Criteria and prediction methods

2.1. Simple angular criteria

The simplest forms of prediction method use obstruction angles [11, 35] as a basis. Figure 3 shows an example. Obstruction angles like these are usually based on the sun's altitude at noon on a chosen day, typically 21 December. This is easy to calculate; it is 66.5° minus the site latitude. The obstruction angle approach can allow for site slope, provided solar facades face up or down the slope rather than across it. Instead of obstruction angles, spacing to height ratios [4] can be quoted. For example an 18.5° obstruction angle (Munich 48°N at noon on 21 December) corresponds to a spacing to height ratio of 3. However these spacing to height ratios assume a level site.

Setting criterion values for obstruction angles seems intuitively obvious but there are three pitfalls:

(a) Choosing a date and time. Using noon on 21 December means that sunlight will be blocked for the whole of the rest of that day, because the sun will be lower than the critical angle. Figure 4 shows why and also indicates that some sun will be blocked in January and November too. So it is necessary to set a lower criterion angle to ensure access to this mid winter sun [18].

Yannas [35] has perhaps adopted the most scientific approach here. Using computer

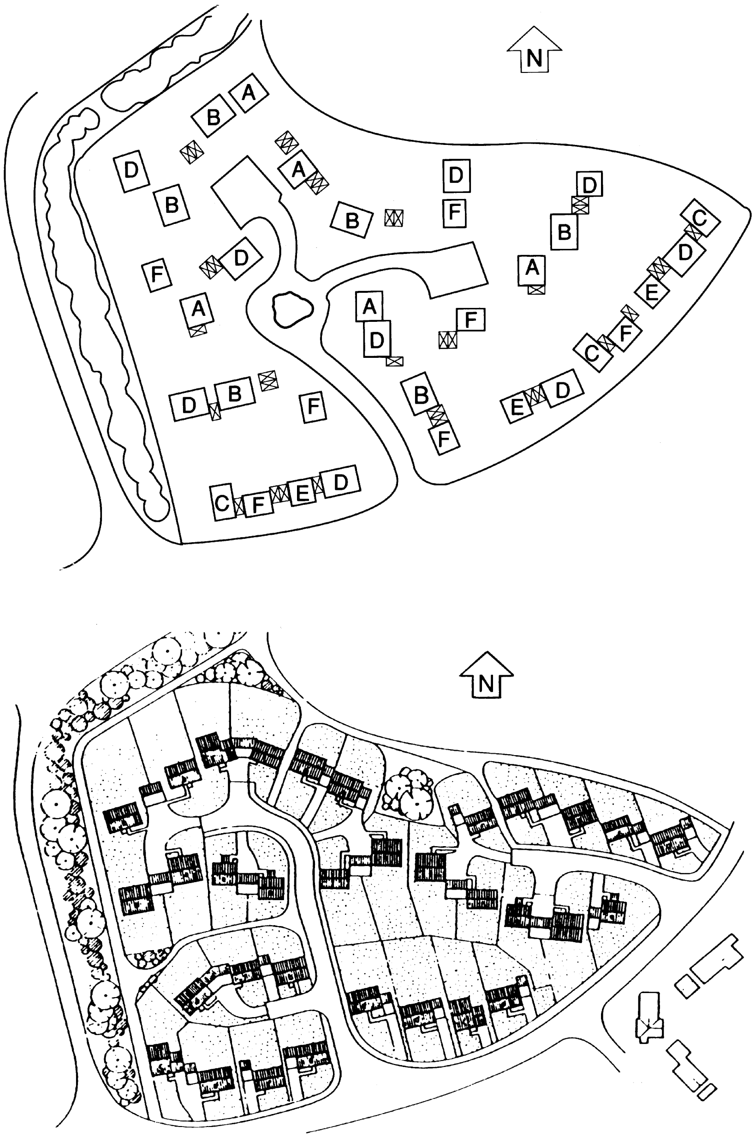

Fig. 2. A site layout design study by NBA Tectonics for ETSU. The conventional layout of detached homes (top) would need 8900 kWh/year for space heating, 8500 kWh/year with passive solar features. The passive solar site layout (bottom), redesigned by Stillman Eastwick-Field, would require only 7900 kWh/year, a saving of over 10%.

simulation, he has obtained obstruction angles which result in 2% or 5% increase in space heating requirements. For London (51.5°N) the 2% value is 13.5°; for 5% increase the critical obstruction angle is 16.5°. These values straddle the 15° altitude of the sun at noon on 21 December.

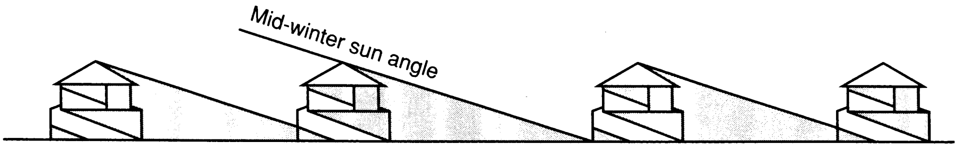

Fig. 3. Using a mid-winter sun angle to space passive solar homes.

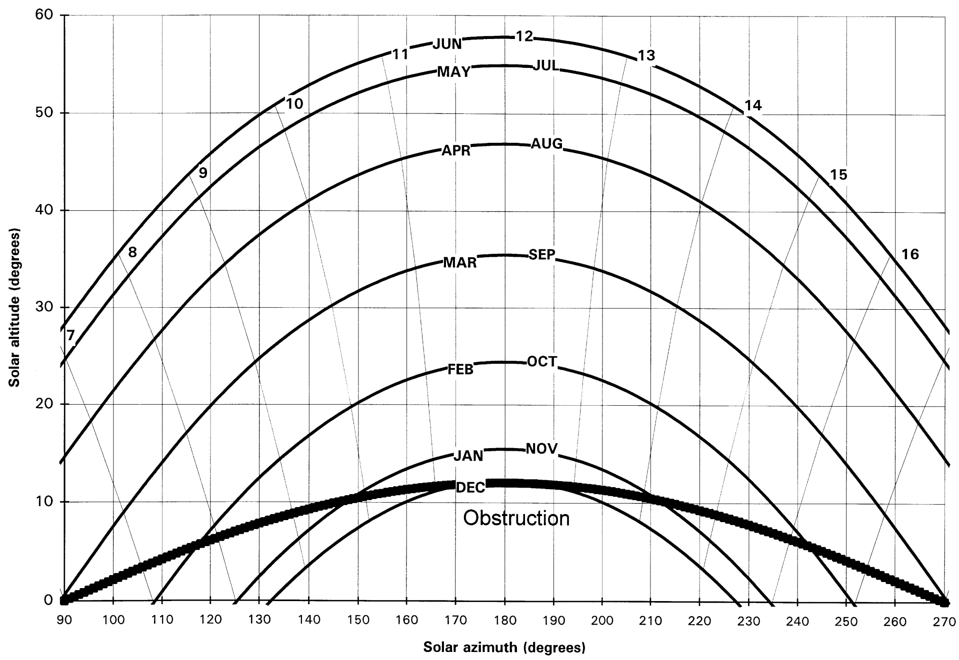

Fig. 4. Sunpath diagram: latitude 55 degrees, showing obstruction parallel to south facing building.

(b) The second issue is where the angle should be measured from. Generally the ground level at the base of the solar facade is taken. This tends to exaggerate the effect of low, nearby obstructions, like fences or single storey buildings. Conversely it will underestimate the impact of tall buildings further away. Daylighting recommendations [8, 18] suggest a 2 m reference height. An alternative is to take the centre height of ground floor glazing.

(c) The final issue is that of facade orientation. Figure 3 assumes the sun is perpendicular to the building. This will be true for a south facing wall at noon, but not for any other orientation.

Most passive solar guide books recommend a southerly orientation [4, 13, 18, 35]. The consensus seems to be that within 20–30° of due south is best. NBA Tectonics have calculated the impact of facade orientation on the heating needed by solar houses

(Figure 5). As well as the loss of solar gain there can be extra problems shading east or west facing glazing in summer.

For non-south facades the conventional obstruction angles in fact work reasonably well. Figure 6 shows why. The winter sun hits the facade obliquely, coming along the road between terraced obstructions. In winter, the sun is never straight above the nearest portion of the obstruction, directly opposite.

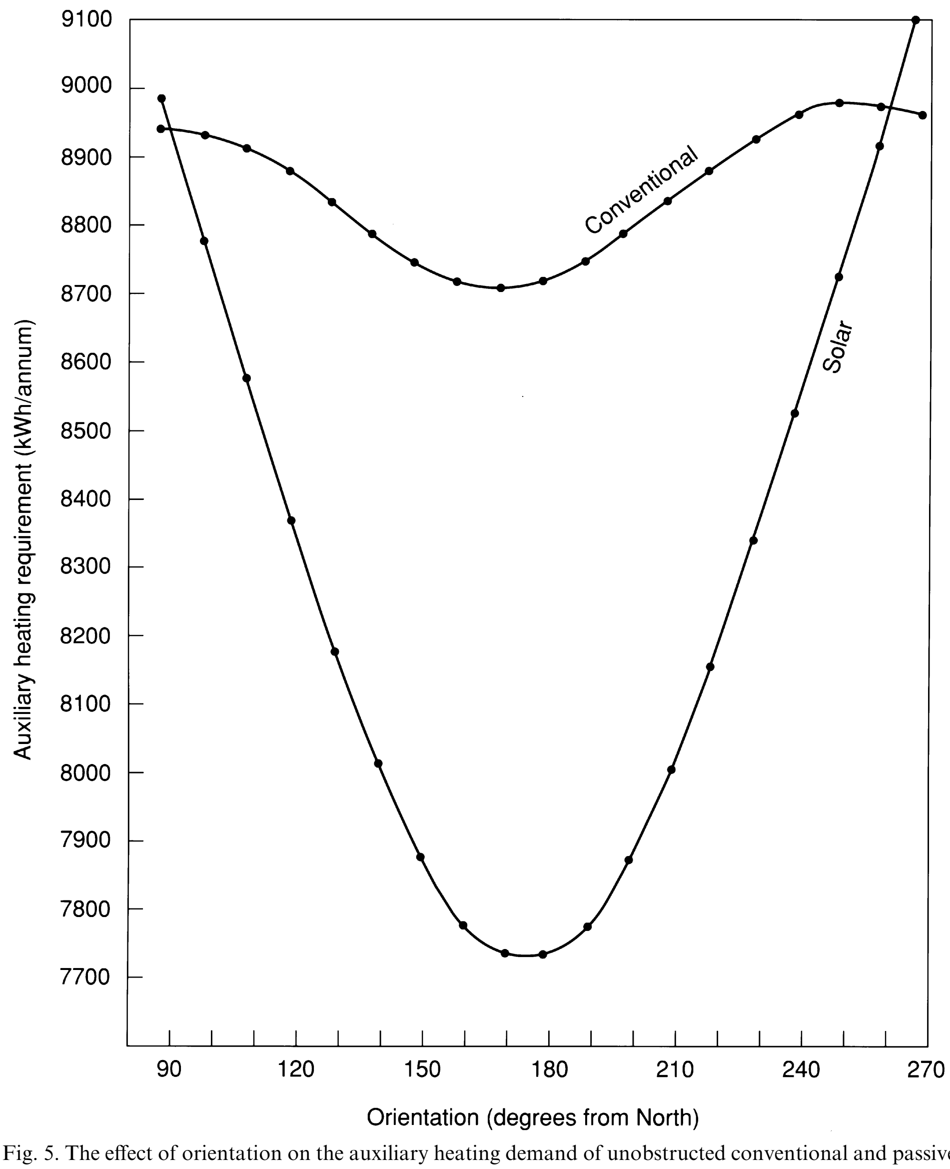

Fig. 5. The effect of orientation on the auxiliary heating demand of unobstructed conventional and passive solar homes (from NBA Tectonics [26]).

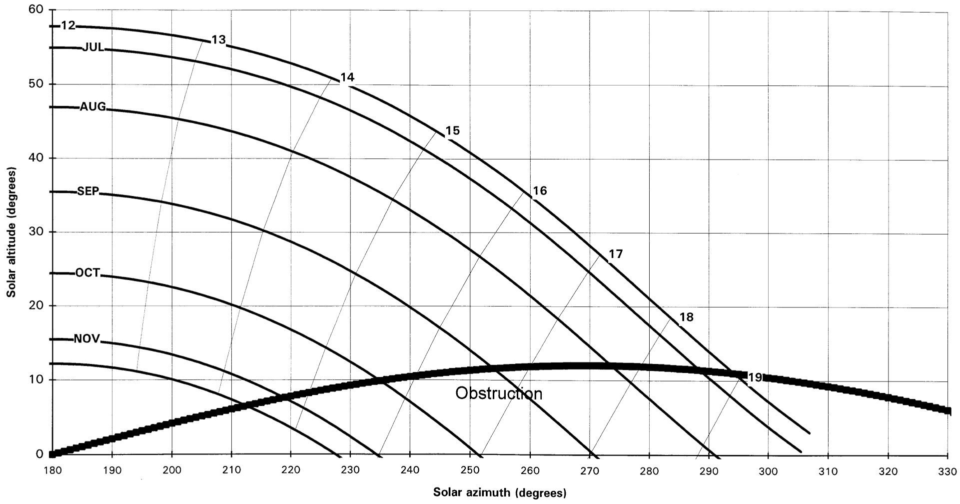

Fig. 6. Sunpath diagram: latitude 55 degrees, showing impact of obstruction parallel to west facing building.

Of course Fig. 6 assumes that the obstruction is limited to a single long parallel one. Even a small nearer obstruction to the south of an east- or west-facing building can cause a big loss in solar gain. This raises a general problem with spacing angles. In today's cities, it is rare to find buildings arranged in neat rows. There is nearly always something closer, in the vertical section perpendicular to the passive solar facade, than the spacing angles permit. It could be a building in another, perpendicular, street or an extension to another building in the same row. How can we tell if these obstructions are important?

2.2. Angular zones

For this reason Littlefair [18] has used the concept of limiting obstruction height within a particular angular zone on plan. The most important area to keep lightly obstructed is within 30° either side of due south of a solar collecting facade (Fig. 7). For U.K. latitudes at least, this is the part of the sky from which most solar radiation comes in the winter months. To check whether solar access from this zone is retained, draw a north-south section (not necessarily perpendicular to the facade). The altitude of any obstructions in it should not exceed the critical angle h when measured from the centre of the solar collecting glazing. Values of h are given in Table 1. If this obstruction angle does not exceed h then for U.K. latitudes at least 3 h of sunlight around midday are guaranteed for the period specified—provided the sun shines of course. Note that the values of h are given in terms of site latitude. So if solar gain was required all year at a site in London (51.5° N) then the maximum obstruction angle h in Fig. 7 would be $65-51.5 = 13.5°$.

Johnson [16] also uses a form of angular zone in a "solar shading chart" (Fig. 8).

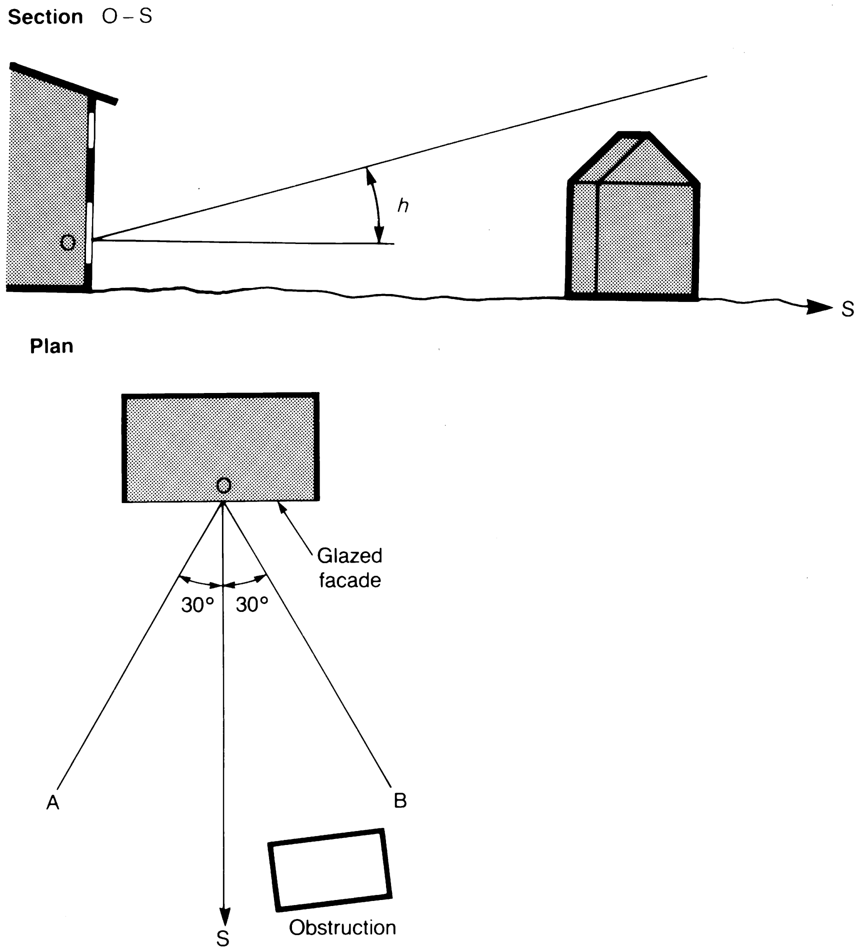

Fig. 7. For passive solar gains in winter the sector AOB 30° either side of due south is important. To guarantee winter sun from this sector obstructions within it should not subtend more than the critical angle *h* when measured in section. Table 1 gives values for *h*.

Table 1
Limiting obstruction angles *h* to ensure at least three hours sun in specified period

Period of year	Value of *h* (degrees)
All year	65 − latitude
21 January–21 November	68 − latitude
6 February–6 November	72 − latitude
21 February–21 October	78 − latitude

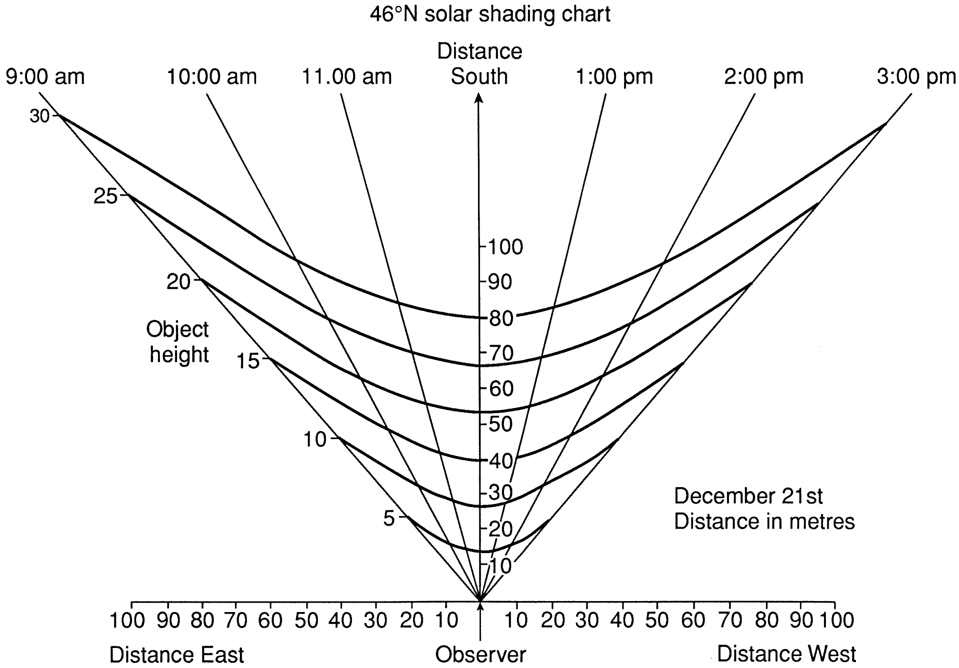

Fig. 8. A solar shadow chart (after Johnson [16]).

This works in a similar way except there is no need to draw a vertical section. Contours of heights of limiting obstructions are given for different distances from the solar building. However the chart is only applicable for one particular day (21 December) and a separate chart is needed for each latitude.

2.3. Sunpath diagrams

Johnson's chart in fact represents a particular, specialised form of sunpath diagram (plotted on a gnomonic projection). A wide variety of these are available. Fig. 9 illustrates a more general gnomonic diagram [18, 21]. The advantages of this projection are that it is relatively easy to plot obstructions from a site plan. Horizontal edges plot as straight lines, and a flat roofed building will keep its shape on plan. It is even possible to place a small stick in the centre of the diagram and use it as a sundial (see Section 2.6. below). The main disadvantage is that very low solar altitudes cannot be plotted on the diagram.

As well as the horizontal gnomonic projection shown in Fig. 9, vertical gnomonic sunpath diagrams are also available [6, 29]. For sunlight on vertical planes, these are perhaps the most intuitive of all to use, as obstructions plot in perspective view as seen from the vertical plane. However a separate diagram is needed for each orientation of the plane.

Equiangular projections [20, 30] (Figs 1, 4 and 6) are straightforward to understand.

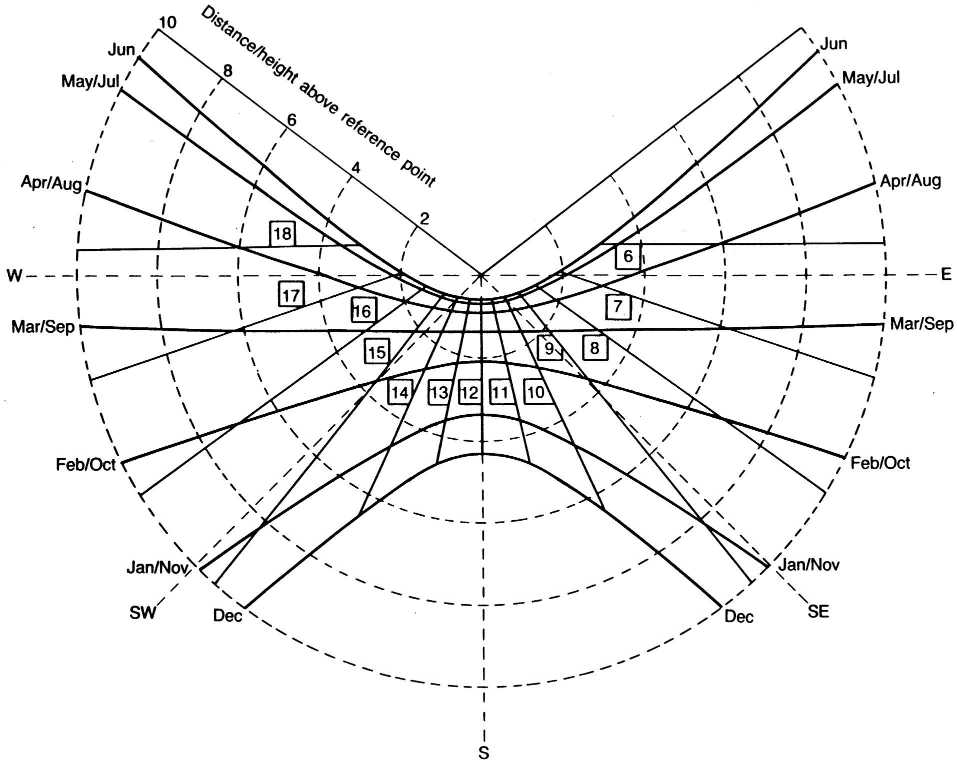

Fig. 9. Sunpath indicator for Manchester (53.5° N).

However horizontal obstructions do not plot as straight lines which can be counter-intuitive. Figures 1, 4 and 6 show how wide horizontal obstructions appear when plotted.

The other widely used type of sunpath diagram uses a stereographic projection [5, 6, 27]. The diagram is easier to construct because sunpaths plot as arcs of circles, but plotting obstructions is relatively difficult.

The output from a sunpath diagram (hours of sun at different times of year) is easy to understand. It is easy to see if a building will have very good solar access, or alternatively if winter solar access will be poor and passive solar design will not be worthwhile. What may be more difficult is comparing different design options in medium density development. Does sunlight between 10:00 and 11:00 in March compensate for the loss of sun between 14:00 and 16:00 in January? What about sunlight that comes at an oblique angle to the solar facade, and may contribute little to solar gain?

2.4. Sunlight availability and solar gain diagrams

These diagrams have been developed to provide more information than the basic sunpath diagram. The BRE sunlight availability protractor [27] gives sunshine probabilities alongside the sunpaths (Fig. 10). In cloudy climates, this avoids the need to design for sunlight that never materialises in practice. Specialist sunlight availability indicators have also been prepared. Littlefair [18, 21] has developed an example based on the same gnomonic projection as Fig. 9. The U.K. British Standard Code of Practice [5] includes a similar diagram based on a stereographic projection. Both diagrams allow winter sun (23 September–21 March) to be calculated separately. However, the criteria given by both authors relate to sunlight for amenity purposes rather than for passive solar gain.

Especially appropriate for passive solar design are diagrams calibrated in terms of solar heat gain through the heating season. Figure 11 shows a "solar gain indicator" developed by Littlefair [18, 21]. This uses the gnomonic projection described in section

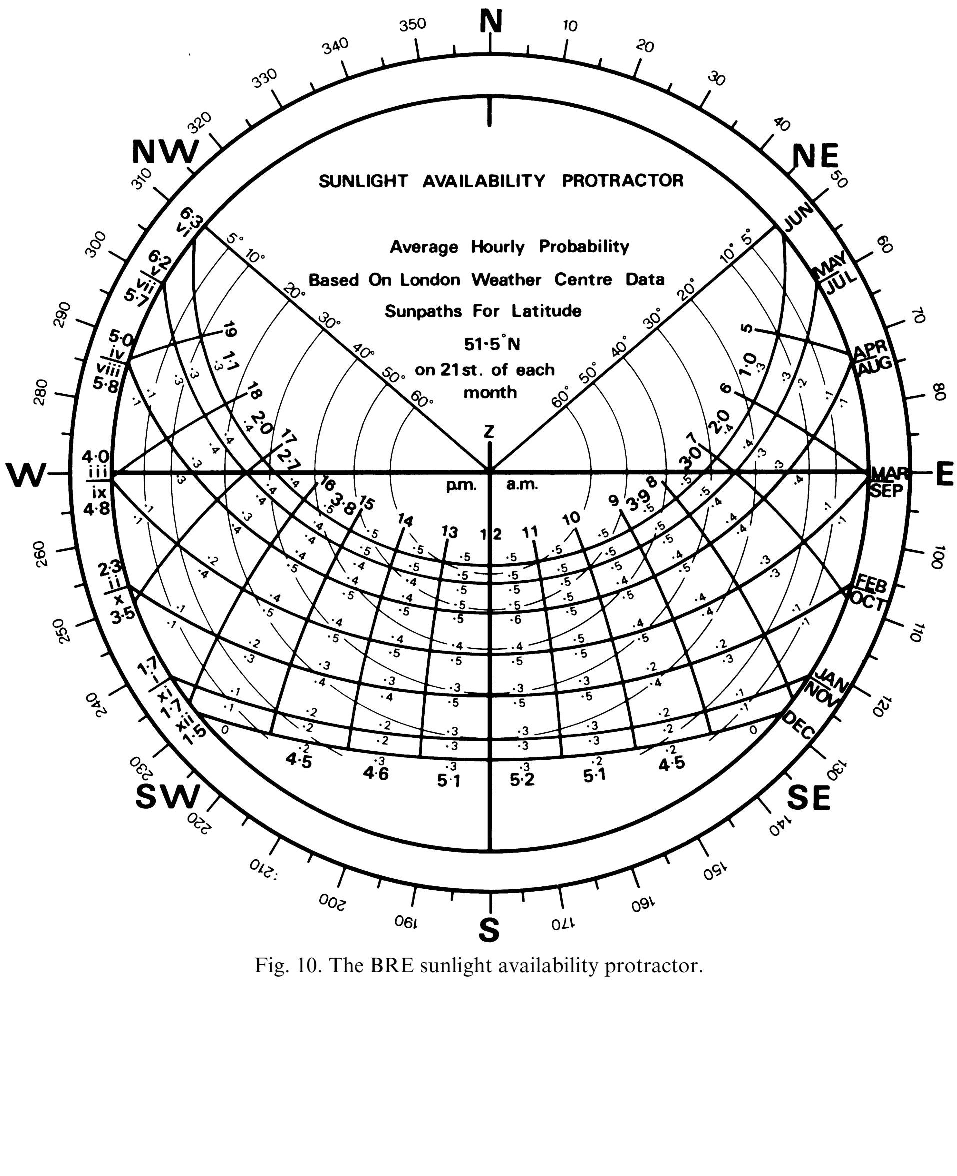

Fig. 10. The BRE sunlight availability protractor.

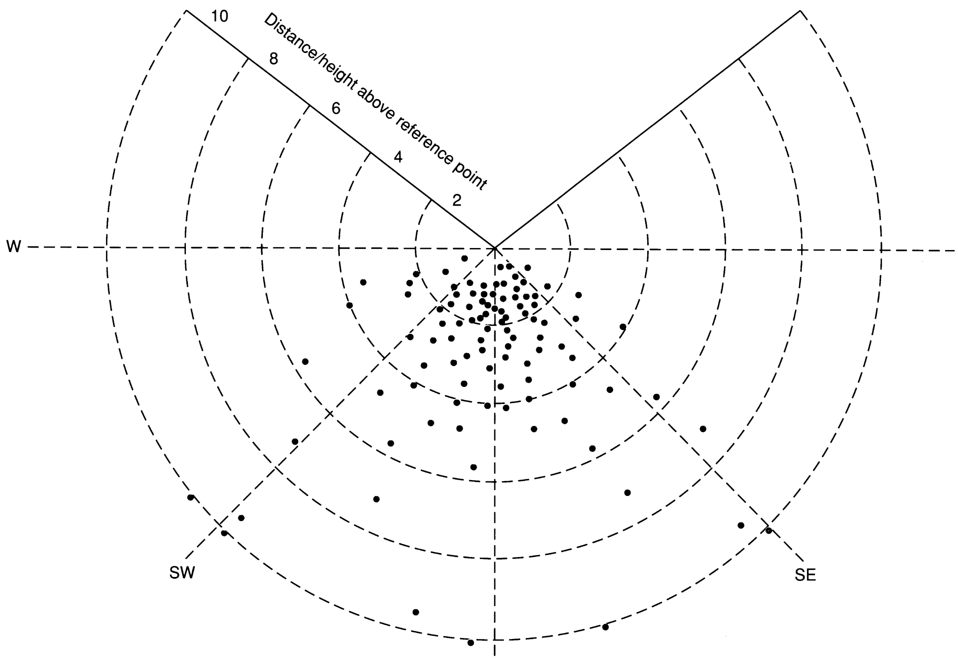

Fig. 11. Solar gain indicator for Manchester (53.5° N). Heating season total for unobstructed south-facing plane = 322 kWh/m^2.

2.3 and can be used in the same way as Fig. 9. Each spot on the diagram represents 1% of heating season solar gain. It is possible both to get an absolute amount of radiation and a comparison with the value for a totally unobstructed window. It is only intended for vertical windows facing approximately due south; it should not be used for sloping glazing or solar panels, or where the window faces more than 30° east or west of due south.

Figure 12 illustrates a "sky map" produced by NBA Tectonics [26]. These divide the area of sky "seen" by a window or other vertical surface into a number of cells, each labelled with the useful radiation receivable from it. The heights and positions of obstructions affecting a point are first assessed on plan, then these data are plotted on to a sky map. The increase in auxiliary heating requirement can then be calculated by summing the radiation amounts from the cells in each column (Fig. 12). Sky map diagrams have been produced for surfaces W, SW, S, SE and E, in two sets containing useful solar gain data for passive solar and conventional houses.

Both diagrams include diffuse solar gain as well as direct, with realistic models for the distribution of solar radiation over the sky vault. This is particularly important in cloudy climates. In southern England diffuse sky radiation accounts for over 50% of the solar radiation reaching the ground in winter, and just under 40% of solar radiation on an unobstructed south facing plane. So it is important to take account of this component, particularly in dense urban sites where every bit of solar gain is

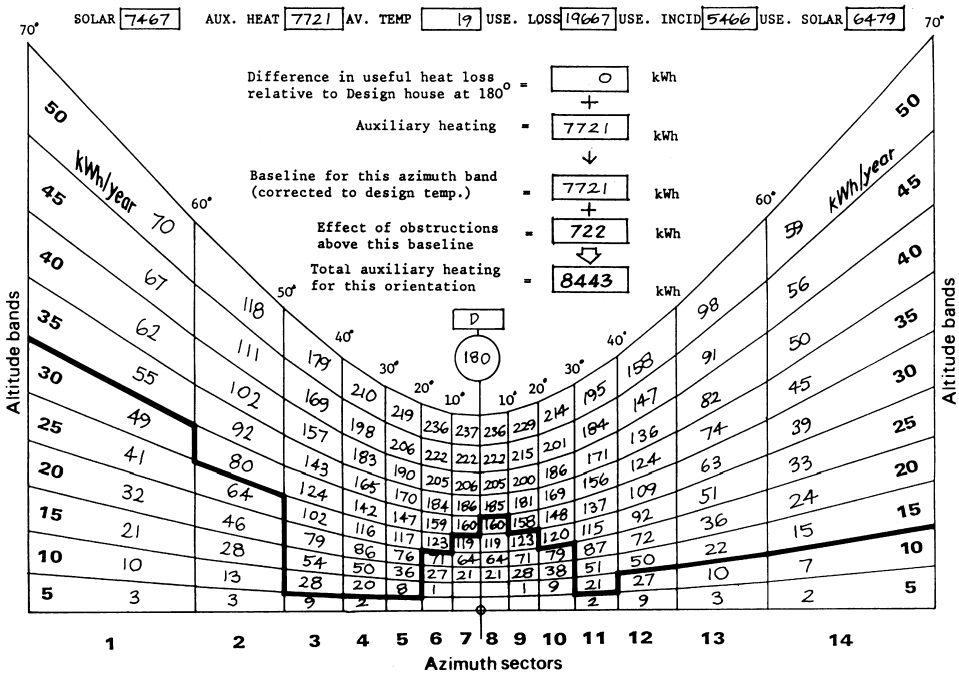

Fig. 12. A solar gain diagram constructed by NBA Tectonics, including an example obstruction.

important. However neither method includes an allowance for radiation reflected from the ground or obstructions.

This approach allows the viability of a passive solar design to be examined in detail, so it should be especially useful in heavily obstructed urban situations. Although there is no published criterion value for solar access, NBA Tectonics' work [26] enables a limited comparison between the heating performances of a solar house and an equivalent conventional house.

2.5. Shadowing studies

The methods described so far all quantify the sunlight or solar gain *received* by a particular building. It is also possible to approach solar access problems from the opposite point of view, and examine the sunlight *blocked* by the building and the shadows it casts. This type of study could be useful in examining the impact of a new development on surrounding buildings or nearby open spaces. It can also be used in the layout of housing estates, to keep each house out of the shadow of the others.

Matus [24] shows how to carry out a shadow casting analysis of a series of buildings. For each building the shape of the shadowed area from 09:00–15:00 during a particular day is constructed (Fig. 13). Matus prefers 21 December as a criterion, but also gives examples for 21 January/21 November and 21 February/21 October. In housing estate design the individual dwellings and their shadow patterns can then be

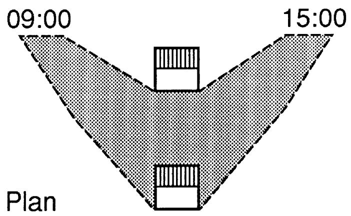

Fig. 13. Spacing south facing houses to avoid the shadowed area on December 21 (Matus 1988)

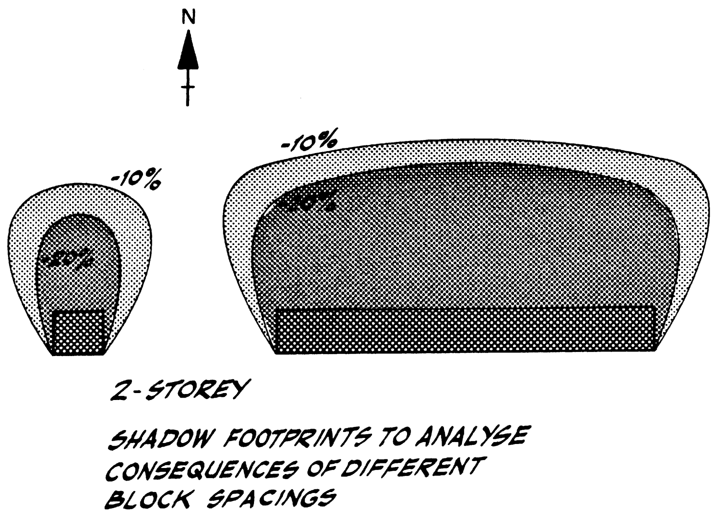

Fig. 14. Solar "Shadowprint" (flat ground).

moved about so that no dwelling lies within the shadow of another. Because of the shape of the shadowed area on 21 December this approach encourages building houses directly opposite each other (Fig. 13) which is not ideal for daylighting or privacy. Another problem is that shadow casting analysis is much more difficult on sloping sites.

The Open University [12] have developed a similar tool based on loss of solar gain. The solar "shadowprints" show how much solar access would be lost at a point in the shadow of an object of fixed size and position. These have been produced as manual design aids specific to a particular ground form (level or sloping) and scale and drawing (Fig. 14). This example includes the reduction in useful radiation through a south-facing, vertical, single-glazed window (i.e. taking account of glass transmission at various angles of solar incidence).

2.6. Model studies

Both shadowing and sunlight penetration studies can be carried out using scale models [19]. Scale models can be used to assess a range of different designs at the same time, simply by adding or removing model buildings. It is also possible to build a visual record (in the form of photographs or even video) of the sun patterns on a site at different times. Either the real or an artificial sun can be used.

Using a lamp to represent the sun has two big advantages. The study can be carried out under any sky condition or even after dark, and it is possible to move the "sun" relatively easily to simulate different times of day and year.

Various types of heliodon are available. An older type [14] involved a lamp which moved up and down to represent the different times of year. The model was then placed on a turntable, tilted according to the latitude of the site, and rotated to simulate different times of day. Now, computer controlled facilities [33, 34] are available which allow the model to be rotated on a horizontal plane while the light source moves up and down; the computer calculates the solar geometry.

However it is possible to use any small, powerful lamp to represent the sun (a theatre spotlight is ideal). By moving the lamp up and down and rotating the model it is possible to generate different sun positions [2, 3]. A small sundial [23, 25], mounted on the model, will indicate when the right time of day and year has been reached. The main disadvantage of an artificial sun is that its rays are not parallel. If the "sun" is too close to the model, it may apparently be a different time of day and year in different areas of the site. For best results the lamp should be at a distance of at least five times the model dimensions.

The real sun can also be used. Under the right weather conditions, there is no problem generating enough light or ensuring the sun's rays are parallel. However the model must be tilted and rotated to represent different times of day and year (a sundial is essential here). This limits the size of the model and everything on it must be securely fixed. It can also be difficult to access the model for visual assessment at a range of different tilt angles.

2.7. Solar envelopes

The solar envelope [17] gives a limiting volume a building can occupy on a site without significantly overshadowing neighbouring sites. Figure 15 shows an example. Goulding *et al* [13] give a simple explanation of how to generate a solar

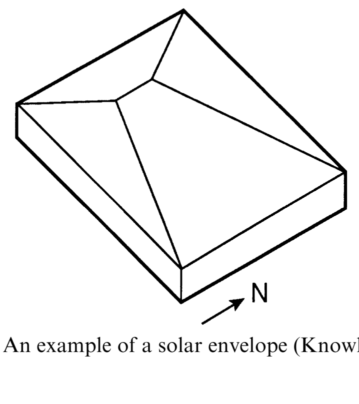

Fig. 15. An example of a solar envelope (Knowles [17]).

envelope. Knowles [17] goes into much greater detail with a number of different examples.

The solar envelope is a versatile concept; Knowles gives a range of different criterion options. Different periods of day and different months of the year can be chosen. The solar envelope can extend to the boundaries of the site, to avoid all shadowing of adjacent site or it can be constructed just to prevent overshadowing to the window walls of nearby buildings.

This approach is especially relevant to protection of adjoining urban land since it can ensure solar access to the whole of neighbouring sites. However it may be too strict a control in tightly packed urban sites where buildings are necessarily close together. This is particularly true far from the equator where solar envelopes can have very little volume if they are to safeguard winter solar access.

2.8. Computer methods

For sunlight analysis, three specialist programs are available, all originating from outside the UK. SHADOWPACK [28] was developed at the CEC research centre in Ispra, Italy. It uses its own CAD-type program to generate a layout. The layout can then be evaluated to give amounts of direct solar radiation received by surfaces. These can be plotted as contour maps. A view of the site can also be generated with the shadows at any particular time of day and year.

TOWNSCOPE [9] was developed at the University of Liege as part of a research programme on urban renewal. It enables the 3D representation of a layout; direct solar radiation on surfaces can be calculated for particular days or months, or for the whole year. The incident sunlight can be plotted on different projections. It incorporates an energy evaluation module. Figure 16 illustrates an example.

GOSOL (available from P Goretzki, University of Stuttgart, Keplerstrasse II, D-7000 Stuttgart 10) enables site layouts to be input and analysed. The energy balance on particular surfaces can be calculated. Shading patterns can be visualised. GOSOL can also produce an outline of obstructions on a sunpath diagram, indicating graphically the times of day and year when the sun can shine on a point in a layout.

The availability of direct sunlight can be assessed using most 3D CAD packages. These generally allow viewing of a development from different angles. If the position of the sun at an important time of year is chosen as the angular viewpoint, the resulting view will include all the building elements which can receive direct sun at that time.

Generally the major weakness of current computer programs lies in their treatment of diffuse radiation, and reflected radiation from the ground and obstructions. Some programs do not include diffuse radiation at all; others include it but assume it is not reduced by obstructions; one or two include it but assume the sky is isotropic. Given the importance of diffuse radiation in cloudy climates (section 2.4.) this is a serious limitation. Under the POLIS project the University of Liege is currently extending TOWNSCOPE to give a more realistic calculation of diffuse sky radiation.

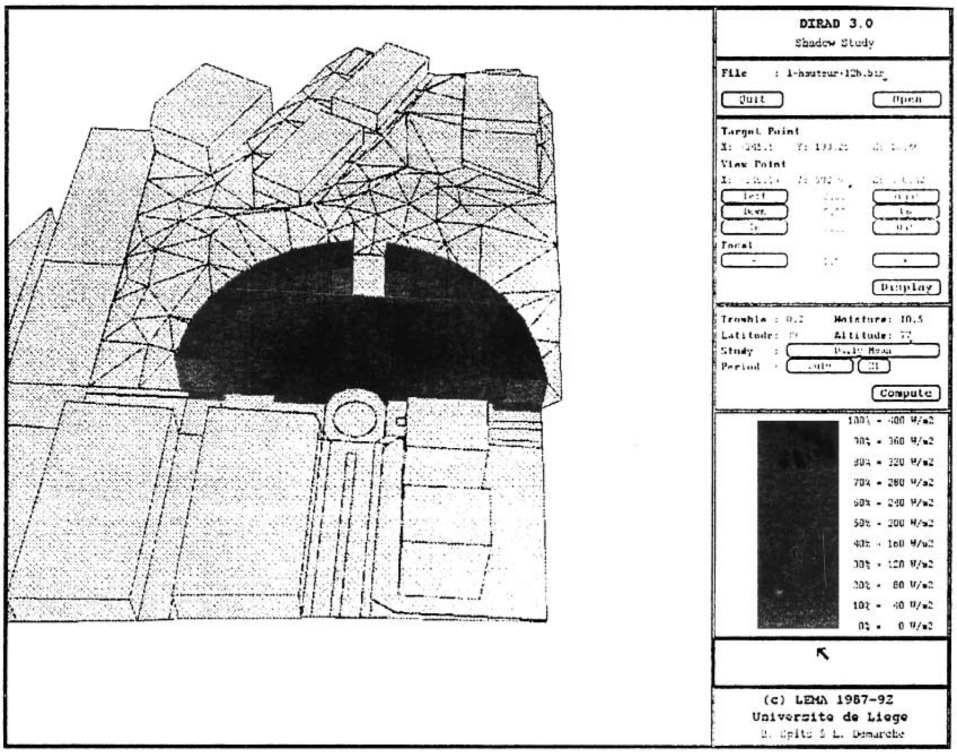

Fig. 16. Example output from TOWNSCOPE showing distribution of direct radiation on a building facade.

3. Discussion

3.1. Evaluating solar access on high density urban sites

Section 2 has described a wide range of methods to calculate whether passive solar gain is available within a site layout. However many of these techniques were originally developed for low density rural or suburban sites. Not all are suitable for high density urban developments, particularly far from the equator where winter sun angles are low.

Nevertheless if passive solar is to become a mainstream urban design option, appropriate design tools are required. In particular, the following would be useful: (i) a simple technique for a first assessment of the site, to establish whether passive solar is feasible; (ii) a more detailed method to compare different design options and assess the exact impact of the various obstructions.

For method (i) the simple obstruction angle techniques in section 2.1. offer the right degree of simplicity. However they may not be feasible in urban sites. First, the generally accepted criterion of midday sun 21 December is not realistic in many northern cities. For London (51.5°N) it results in an obstruction angle of only 15°.

Second, in many urban sites obstructions can be uneven. As well as buildings opposite there can be buildings at right angles and projections from the line of the solar facade. And the buildings opposite may themselves be a range of different heights. Under these circumstances it is almost guaranteed that some part of some building will encroach above the limiting obstruction angle.

There are three ways to overcome this problem:

- define an angular zone on plan (section 2.2.) within which obstructions need to be limited. Obstructions outside this zone can be ignored;
- set a more realistic obstruction angle;
- allow some obstructions to exceed the limited obstruction angle if enough solar gain is available from other directions.

An angular zone is fairly easy to define. The area of the sky between south east and south west includes nearly all the useful direct sunlight in winter. Calculations for a south facing building in London show that three quarters of heating season solar gain comes from this zone of the sky.

Setting a limiting obstruction angle is more tricky. North of 50°N the midday sun angle on 21 January/21 November appears appropriate for urban locations. This is approximately 70° minus the site latitude on a south facing surface. In London (51.5°N), 50% of the heating season solar gain comes from the area of sky above this angle between south-east and south-west directions. In Edinburgh (56°N) the proportion is over 70%.

However nearer the equator this obstruction angle (70° − latitude) is perhaps too high. The heating season is shorter so solar gain in January, November and December is important. Also the larger obstruction angle results in much of the diffuse solar gain being lost. Consequently it is suggested that for latitudes south of 46.5°N the 21 December midday solar altitude be chosen. This gives an obstruction angle of 66.5° minus site latitude. Between 46.5°N and 50°N a 20° obstruction angle could be used. In a densely packed urban site it seems sensible to take the angle from the centre of the glazing rather than the foot of the building. Figure 17 summarises this guidance.

An angular criterion like this can be useful at the early stages of building layout. If all the obstructions in the SE–SW zone are below the limiting angle then passive solar design should be feasible. If they are all above the limiting angle then it will usually be best to choose an alternative design strategy, or to build somewhere else. However often some of the zone will include obstructions above the limiting angle and some will be more lightly obstructed. In these circumstances a more detailed calculation technique will be required.

Here a solar gain calculation should be appropriate. Of the two manual techniques reviewed in section 2.4., the NBA Tectonics sky map [26] is only available for U.K. latitudes, although there are diagrams for different facade orientations. The solar gain indicators [18] are for south facing glazing only, but it should be easier to plot the obstructions and indicators will soon be available for locations throughout Europe [21]. An alternative is to use a computer-based technique, but it needs to treat the diffuse radiation blocked by obstructions properly. The extension to TOWNSCOPE, currently underway, should make it very suitable for this purpose.

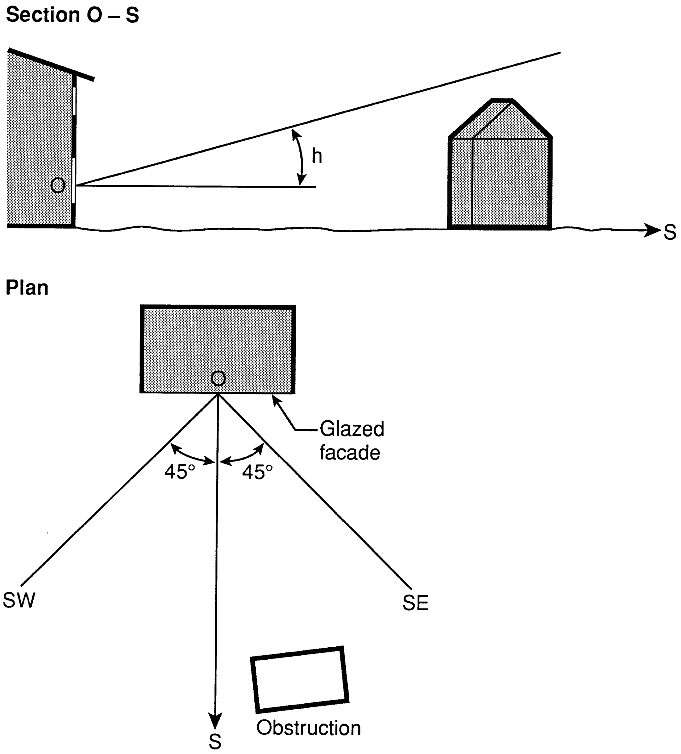

Fig. 17. For solar access in urban areas the area of sky between south east and south west becomes important. Obstructions in this zone should ideally not exceed the critical angle h. For latitudes above 50°, h is 70° − latitude; for latitudes below 46.5°, h is 66.5° − latitude; for intermediate latitudes h is 20 degrees.

3.2. Loss of solar access to existing buildings

As solar design moves into the city and becomes more widely established, the issue of loss of solar access to existing buildings will become increasingly important. Yet outside the United States at least, this issue has not been widely addressed.

A key question here is how any measures on loss of solar access are to be implemented. There are conflicts of interest here. On the one hand, existing owners rely on solar access for the effective operation of their buildings. Blocking it will result in financial loss, both in extra energy bills and in the reduced capital value of the property. Comfort and amenity value of the building can also be reduced. However adjoining owners also need to be able to develop their sites. There is a pressing need for new homes, workplaces and public buildings like schools and hospitals, and it is better to develop urban sites than use up rural land.

Should protection of existing buildings just apply to solar ones? There are arguments against this: (a) Ordinary buildings benefit from solar gain too. It is unfair to allow loss of solar access to them and not to a specialist solar building; (b) Defining a solar building thus becomes an issue, particularly with passive solar which may not have obvious bolt on features. How do you tell a passive solar house from an ordinary one with large windows and a conservatory? (c) Construction of a solar building could cause a big drop in the value of adjoining land; (d) Ordinary buildings could be retrofit with solar measures, turning them into solar ones. If this then restricted the ability of adjoining owners to build, the value of adjoining land could drop suddenly. In extreme circumstances, building owners who wanted to preserve their outlook could invest in solar measures with the sole purpose of restricting adjoining development.

Arguments (c) and (d) could be dealt with to some extent by adopting a precedent from English rights to light law [1, 10]. The right to light is a legal right which one property may acquire over the land of another. If a building or wall is erected on this land which reduces the light in the obstructed property to below sufficient levels, then the right to light is infringed. The owner or tenant of the obstructed property may sue, either for removal of the obstruction or for damages. Rights to light can be acquired if the light has been enjoyed without interruption for at least 20 years. It would be possible to enact similar legislation to protect solar buildings. If a solar building had enjoyed a particular level of solar gain for a set time (which need not be as long as 20 years) it could acquire a right to solar access. However there is still the problem of defining a solar building. Also such time activated rights can lead to unusual legal consequences. Under English rights to light law, if the light is obstructed for more than a year then the right is usually lost. In the past, if windows had received light over adjoining land for nearly 20 years, the owner of the adjoining land could erect an obstruction like a large advertising hoarding to block the light and prevent a right being acquired. This has now been replaced with a system whereby the adjoining owner may register a "Notional Obstruction". This exists only on paper, but is a way of stopping the windows acquiring rights to light over the land when the 20 years is up.

Overall it appears difficult to apply protection of solar access solely to solar buildings. The simple option is to apply it to all buildings that make some use of solar gain. Various options are possible:

(i) *A national building regulation*. Under this option it would be very difficult to address the needs of different types of urban area, from open suburban land to the densely packed inner city where solar access is more restricted.

(ii) *Local planning laws*. These can include zoning of the city or town to allow for different levels of solar access in different types of built up area. Alternatively they can apply only in particular designated areas where renewable energy is specifically encouraged. There may be a problem with the sudden impact of a solar zoning law. Overnight, future development of some sites may become severely restricted resulting in loss to their owners. A way round this is to apply solar access zoning only to areas of the city which are as yet undeveloped and where future development is still at the urban planning stage. Future building owners in those areas will be restricted in how high and wide they can build. But they will also have the benefits of guaranteed solar access.

(iii) *Private legal agreements*. There are various situations in which these could apply. When a solar estate is constructed a legal agreement could be drawn up protecting future solar access for each property. To own a house on the estate it would be necessary to sign this agreement. Alternatively the owner of a solar building may sell adjoining land on condition that future development there does not block solar access to the original building.

Nearly all the work on protecting solar access appears to come from the United States, and is mainly aimed at protecting active solar collectors. Knowles [17] advocates use of his solar envelope technique (section 2.7.) as a measure in city zoning. This ties in with U.S. planning practice where conventional zoning procedures often limit the height of buildings in particular areas. The solar envelope protects adjacent land for future development as well as existing buildings. However as section 2.7. points out, it may be too strict for latitudes far from the equator and on densely packed urban sites. Also, on oddly shaped sites the solar envelopes can become complicated, and compliance may be difficult for planning authorities to verify.

Tabb [32] reviews different techniques for solar zoning, including the solar envelope. He also describes the bulk-plane method of zoning, which limits development to below a sloping plane which rises up from the north of the site. Effectively this is equivalent to a limiting obstruction angle in a north-south section, similar to that shown in the top half of Fig. 7. However here the angle is measured from ground level at the site boundary. This approach also seems less appropriate for densely packed urban sites where there is pressure to build close to boundaries, and it prescribes a particular building form. Its main advantage is simplicity.

The city of Boulder, Colorado, has adopted the "solar fence" method [32]. This involves an imaginary fence placed around the site of the new building. The new building is not allowed to cast a shadow over the solar fence at critical times; these are 10:00 12:00 and 14:00 on 21 December. The solar fences are fairly high; 15 ft for low density and 25 ft for high density residential areas. As Tabb [32] points out this can in fact result in protection only being generally provided for roof access, with some loss of sun for side windows. Jaffe and Erley [15] review a similar solar ordinance in Los Alamos, New Mexico, where the solar fence is 12 ft high. They note the high degree of restriction on adjoining development and conclude that "it is unlikely that this zoning technique would be applicable to districts other than single family detached or low rise attached housing". At high latitudes the restriction would be even greater.

All of the above are zoning measures which apply regardless of the geometry of existing buildings next door, or even whether there is an existing building at all. Tabb [32] also gives a draft of a "solar covenant" drawn up to protect a specific building from loss of sun. This is designed to ensure completely unobstructed sun to a specific "solar collection device or devices" between 09:00 and 15:00 every day of the year. For passive solar the "collection device" could be a window. Jaffe and Erley [15] quote a Colorado Springs ordinance prohibiting shading of a solar collector between 10:00 and 14:00. As they point out, using the location of the collector area to define solar access means that just the right amount of protection is provided and unnecessary restrictions on the neighbour are avoided.

The examples quoted above come from the south west United States. Solar access planning is relatively easy to implement there because: (a) the latitude is relatively low and so winter solar access is fairly easy to ensure; (b) more land is available so buildings can be spaced out; (c) there is a regular rectilinear plot structure.

For urban areas in other countries, further from the equator, the regulations and covenants quoted above will probably be too restrictive. In particular, the requirement that no part of any new development can cast shadows in the specified areas at the specified times is inflexible. Jaffe and Erley [15] discuss possible exemptions for chimneys, TV aerials and similar slender structures. Even with these exemptions, ensuring solar access for 4 h on 21 December is not usually feasible in an urban site in, for example, Northern Europe. An alternative is to choose a different target date, say 21 January. However this can lead to anomalies. Suppose obstruction A cuts out only 5 min of sun both on 21 January and throughout December. This is clearly preferable to obstruction B which cuts out all the December sun while leaving the existing building unshaded on 21 January.

Previous work at BRE [18] could provide the basis for a more flexible method. This earlier work concentrated on protecting daylight to existing buildings. The process is a two stage one. The initial criterion is the angle to the horizontal subtended by the new development at the level of the centre of the lowest window. If this angle is less than 25° for the whole of the development then it is unlikely to have a substantial effect on the diffuse skylight, or the amenity value of sunlight, enjoyed by the existing building. If, for any part of the new development, this angle is more than 25°, a more detailed check is needed to find the loss of skylight and sunlight to the existing building.

Any reduction in the total amount of skylight can be calculated by finding the vertical sky component at the centre of each main window. The vertical sky component is the ratio of the skylight illuminance on the window wall to the illuminance on unobstructed horizontal ground. The maximum value is almost 40% for a completely unobstructed vertical plane. If this vertical sky component is greater than 27% then enough skylight should still be reaching the window of the existing building. If the vertical sky component, with the new development in place, is both less than 27% and less than 0.8 times its former value, then occupants of the existing building will notice the reduction in the amount of skylight. The area lit by the window is likely to appear more gloomy, and electric lighting will be needed more of the time.

A possible analogy to this for solar access could go as follows: (i) use the angular zone criterion outlined in the previous section (obstruction angle at centre of solar façade less than 70° − latitude within zone between SE and SW, Fig. 17); (ii) if the above criterion is not met with the new building in place then calculate the heating season solar gain with and without the new building in place using one of the methods in sections 2.4. or 2.8. If the solar gain is more than 0.9 times its former value then the reduction is small.

This technique gives unrivalled flexibility but there are dangers, particularly in accepting what could be the first of a series of small losses to the available solar gain. This could happen where successive extensions are planned to the same building. Here the total impact on solar gain due to all the extensions needs to be calculated and compared with the guidance above.

In summary, for existing buildings the best technique appears to depend on the context. The relative reduction technique outlined above can work well for general planning situations where existing buildings already have a wide variety of levels of solar access. However, when a solar estate is constructed with legal agreements to protect solar access for each property, it is probably best to define an area of the sky into which no future obstruction can encroach. This should be realistic. It should rule out future buildings which would cause a serious reduction in solar gain to an adjoining property, but not prevent smaller buildings which would have little or no impact on solar access. Obviously, the criterion should be met with the solar estate as initially constructed. One way to ensure this is to use the same guidelines that were used in designing the estate in the first place.

4. Conclusions

A number of techniques are available for predicting solar access in obstructed sites. Most concentrate on sun position only. There is a need for methods which can provide more information about the resulting solar gains, particularly computer tools. Under the POLIS project extensions to the University of Liege's program TOWNSCOPE will enable it to model diffuse radiation as well as direct solar gain. Additionally, manual solar gain indicators are being developed for a range of European locations. These tools can also be used to assess the loss of solar gain to existing buildings following construction of new development nearby.

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