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Solar radiation and urban design for hot climates

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Abstract. Three archetypal building forms, termed the pavilion, street, and court are evaluated and compared in terms of their thermal performance when they are realised as non-air-conditioned buildings in a hot climate. Techniques for calculating the solar exposure of buildings are reviewed, and a new technique is described which is applicable to arrays of archetypal building forms. A number of conclusions are reached which suggest appropriate urban forms and building dimensions for both hot and composite climates.

It is well known that, in overheated regions with a desert climate, exposure to solar radiation is the main cause of overheating of buildings. The designer of an individual building in an urban context uses various devices like sunshades to prevent excessive solar heat gain to the building, but he has little control over the form and size of the surrounding buildings. Traditionally, however, the collective need of all buildings for sun protection was one of the major forces that decided the urban form. This is clearly seen in the town plan of Jaisalmer in India (Gupta, 1981), where each individual building was placed in a well-protected environment. In recent times several studies have been made of wind-induced convective heat loss and of solar heat gain to buildings in cold climates, but similar studies are not available for the hot regions.

A number of researchers have analysed the effect of building form on solar radiation heat gain but such studies (Olgyay, 1963; Markus and Morris, 1980; Sahu. 1982) have mostly concerned themselves with individual buildings. Knowles (1974) has studied building groups and the resultant solar shading from the point of view of maximising winter solar heat gain while minimising it in summer. Although this is desirable for places with a mild summer, there are many hot regions where winter heating needs are minimal and the critical need is only to reduce summer heat gain. In a study of the thermal environment prevailing in Jaisalmer (Gupta, 198 1), it was seen that the air temperatures in the streets were several degrees lower than the air temperatures around buildings outside the town. Other factors being equal, this difference can arise only from the layout of the buildings. Thus, it is important to investigate how urban design can help in minimising heat gain to individual buildings.

Olgyay (1963) has studied the optimum building shapes for different climates. His analysis, which takes into account heat load due to solar radiation, shows that least-surface-area buildings with square plan are not the optimum solution for any climate. Elongated building plans with the longer axis oriented east-west have a better thermal performance than square buildings. Olgyay also refers to the beneficial effect of large mass with less surface area in cold and hot-arid climates. The implication of these two requirements for good building layout is that in extreme climates buildings should be put close together to present less external surface area to the outdoor environment and that the overall form of the building group should be elongated along the east-west direction.

Hawkes (1981) has shown that, since building envelopes consist of materials with very different characteristics (glass, for instance, has high thermal. transmittance and is transparent to solar radiation, whereas opaque walls can have low thermal transmittance) and are exposed to a nonuniform radiation environment, an optimum building form that permits favourable interaction between the internal and external environments can be determined. Such a form will differ greatly from the least-surface-area cube. According to Hawkes, a cube-like fortn is useful only when the window area per unit of building envelope is 0.

Yet the notion persists that compact building forms have a better thermal performance (Peach, 1981). Markus and Morris (1980) have shown that a low surface-to-volume ratio results in lower heat losses from buildings, and Sahu's study (1 982) of air-conditioned buildings in hot climates also gives similar findings.

It is lily contention that the above is not necessarily true of non-air-conditioned buildings in hot climates and that the shapes and orientations that are optimum for single buildings do not necessarily remain optimum when repeated in urban layouts. In non-air-conditioned buildings the heat flow is inwards during the day and outwards during the night, as opposed to the unidirectional heat flow in an air-conditioned building. In urban layouts. the shadowing of one building by another can create situations where the radiation environment around a building becomes substantially different from that around an unshaded building. For these two reasons. it is necessary to see if the design guidelines arrived at after a study of air-conditioned single buildings remain meaningful for non-air-conditioned buildings in clusters.

Real buildings take on different forms which can be very complex. and it is not the purpose here to analyse any specific building form from a solar radiation viewpoint. Apart from the basic structure. real buildings may also have various kinds of shading devices, fixed or movable. The effect of such devices. and the design procedure for 1978). Such devices can be used to improve the performance of any building. sunshading devices are normally employed over window openings only and do not affect the overall exposed area of the building. Obviously. if the basic building form is well conceived to minimise exposure. sunshading devices will improve its performance even further. Our concern, therefore, is to find efficient building forms.

Building forms

Martin and Marc Il (1972) have carried out a general analysis of building forms from the point of view of land utilisation. They have classified buildings into three basic Types, that is, Pavilions, Streets, and Courts[1] (figure l). *Pavilions* are isolated Buildings, single or in clusters, surrounded by large open spaces. For the sake of simplicity. It is assumed that such buildings are square in plan. The *Street* is long

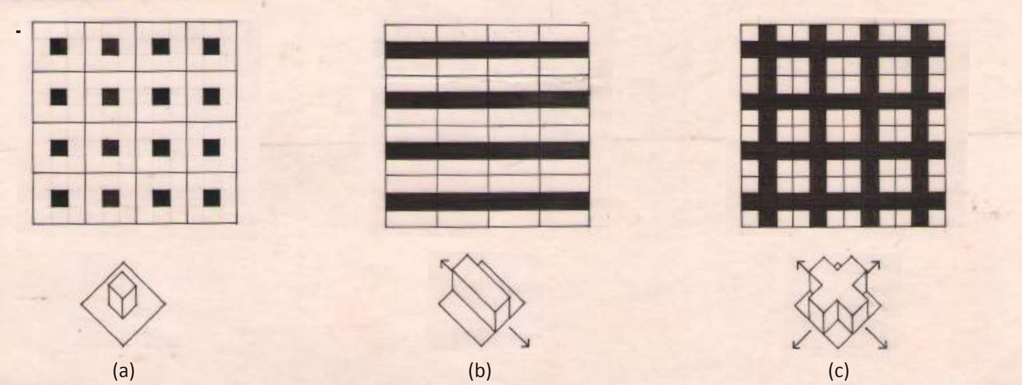

Figure 1. Three different dispositions of built forms: (a) Pavilion, (b) Street, (c) Court

1 Capital letters have been retained for building types to distinguish them from actual streets etc

building blocks arranged in parallel rows, separated by actual streets or just open spaces. *Courts* are defined as open spaces surrounded by buildings on all sides. Although Pavilions and Streets are simple enough to visualise in terms of real buildings, it is a bit difficult to see how a Court form, as described by Martin and March. becomes a group of buildings. But, if the Court is seen not as a 'cross' but as a square building incorporating a courtyard and surrounded by streets or open spaces, it becomes a real building. Each of these three building types (figure 2) are defined by a number of variables.

Type	*Variable*
Pavilion	length, height
Street	length, width, height
Court	length, width, height

When considering groups of buildings (as opposed to single buildings) two other width of the street or the open space between the buildings. The arrangement of blocks in plan also needs to be defined. It is proposed to study the configurations shown in figure 2, where the number of Pavilion and Court blocks is N2 and the Number of Street blocks in N. Thus, N becomes the number of subdivisions or modules in one direction. Rather than define the street by its width, it is possible to express it as a fraction, H/w, equal to building height, H, divided by street width, w.

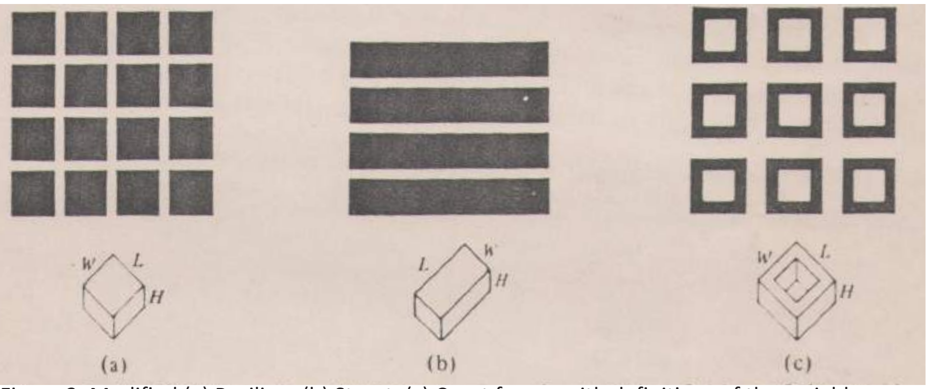

Figure 2. Modified (a) Pavilion, (b) Street, (c) Court forms. with definitions of the variables L length, W width and H height.

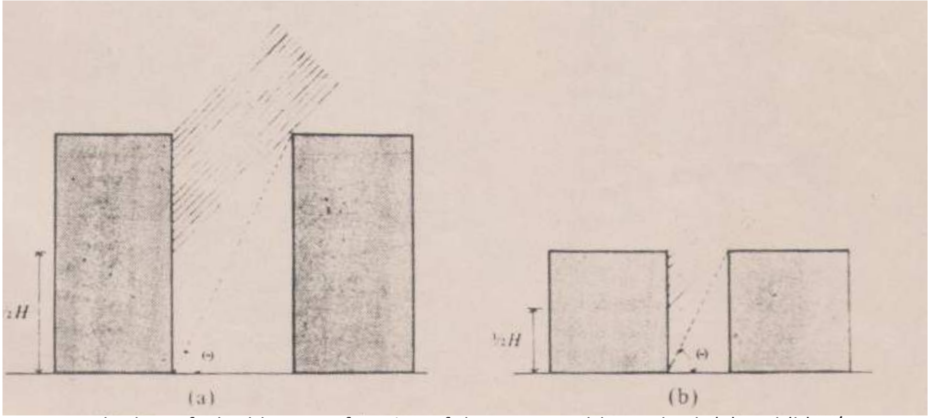

Figure 3. Shading of a building as a function of the street width. For both (a) and (b) H/w (ratio of a building height to street width) is 2 (θ is the angle of obstruction)

This has the advantage that the percentage of overshadowing of one building by another, which is a function of the obstruction angle, Θ, (figure 3) remains constant for different building heights with the same H/w. Also, in real situations, the distance between buildings is usually related to the height, to obtain sufficient daylight and ventilation indoors. The different physical properties of the three building types, expressed in terms of the basic variables, are given in table l.

Table 1. The physical properties of the three building types, expressed in terms of the basic variables L length, H height, W width, N the number of modules in one direction, and H/w is the ratio of height to street width, w.

Type	Variables	Volume [a]	Surface area [a]	Roof area [b]
Pavilion	$L, H, N, H/w$	L^2HN^2	$N^2L(L+4H)$	L^2N^2
Street	$L, W, H, N, H/w$	$LWHN$	$NWL+2H(L+W)$	NLW
Court	$L, W, H, N, H/w$	$4HWN^2(L+W)$	$4N^2W(L+W)+2H(L-W)$	$4WN^2(L+W)$

[a] Of a block

[b] The roofs are flat

Surface areas

To compare the performance of the three building types with respect to the variables. it is necessary to assume a volume and a floor area for a reference building and to generate the possible combinations of the variables. The reference volume needs to be sufficiently large to give various building forms for larger values of N and H. In this study, this reference volume is assumed as 800 000 m3 which is of the same

Table 2. The possible combinations of the variables N the number of modules in one direction, H height, L length, for Pavilions of total volume 800 000 m^3.

N	H (m)	L (m)	N	H (m)	L (m)	N	H (m)	L (m)
1	3	516.398	20	3	25.820	48	3	10.758
1	6	365.148	20	6	18.257	48	6	7.607
1	12	258.199	20	12	12.910	48	12	5.379
1	24	182.574	20	24	9.129	52	3	9.931
1	48	129.099	24	3	21.517	52	6	7.022
1	96	91.287	24	6	15.215	52	12	4.965
4	3	129.099	24	12	10.758	56	3	9.221
4	6	91.287	24	24	7.607	56	6	6.521
4	12	64.550	28	3	18.443	56	12	4.611
4	24	45.644	28	6	13.041	60	3	8.607
4	48	32.275	28	12	9.221	60	6	6.086
8	3	64.550	28	24	6.521	60	12	4.303
8	6	45.644	32	3	16.137	64	3	8.069
8	12	32.275	32	6	11.411	64	6	5.705
8	24	22.822	32	12	8.069	64	12	4.034
8	48	16.137	36	3	14.344	68	3	7.594
12	3	43.033	36	6	10.143	68	6	5.370
12	6	30.429	36	12	7.172	68	12	3.797
12	12	21.517	40	3	12.910	72	3	7.172
12	24	15.215	40	6	9.129	72	6	5.072
16	3	32.275	40	12	6.455	72	12	3.586
16	6	22.822	44	3	11.736	76	3	6.795
16	12	16.137	44	6	8.299	76	6	4.805
16	24	11.411	44	12	5.868	76	12	3.397

order as the built volume of Jaisalmer. Tables 2, 3, and 4 show the range of possible building configurations with this volume, for Pavilions, Streets, and Courts, respectively. Figure 4 shows the variation in the surface areas of buildings with changes in N and H. The roof area of a building cluster (with a given volume), which is independent of the plan form and depends only upon the building height, is also shown. It can be seen that the least surface area is obtained with single Pavilions, and this area is not very much larger than the roof area. For all three types of forms, the surface area decreases sharply as the height of the building is increased from one to four storeys after which the increase in height does not change the surface area very much

Table 3. The possible combinations of the variables N the number of modules in one direction, H height, L length, for Pavilions of total volume 800 000 m^3.

N	*H* (m)	*L* (m)	*W* (m)	*N*	*H* (m)	*L* (m)	*W* (m)
1	3	26666.67	10	28	12	238.10	10
1	6	13333.33	10	28	24	119.05	10
1	12	6666.67	10	28	48	59.52	10
1	24	3333.33	10	32	3	833.33	10
1	48	1666.67	10	32	6	416.67	10
1	96	833.33	10	32	12	208.33	10
4	3	6666.67	10	32	24	104.17	10
4	6	3333.33	10	32	48	52.08	10
4	12	1666.67	10	36	3	740.74	10
4	24	833.33	10	36	6	370.37	10
4	48	416.67	10	36	12	185.19	10
4	96	208.33	10	36	24	92.59	10
8	3	3333.33	10	36	48	46.30	10
8	6	1666.67	10	40	3	666.67	10
8	12	833.33	10	40	6	333.33	10
8	24	416.67	10	40	12	166.67	10
8	48	208.33	10	40	24	83.33	10
8	96	104.17	10	40	48	41.67	10
12	3	2222.22	10	44	3	606.06	10
12	6	1111.11	10	44	6	303.03	10
12	12	555.56	10	44	12	151.52	10
12	24	277.78	10	44	24	75.76	10
12	48	138.89	10	48	3	555.56	10
12	96	69.44	10	48	6	277.78	10
16	3	1666.67	10	48	12	138.89	10
16	6	833.33	10	48	24	69.44	10
16	12	416.67	10	52	3	512.82	10
16	24	208.33	10	52	6	256.41	10
16	48	104.17	10	52	12	128.21	10
16	96	52.08	10	52	24	64.10	10
20	3	1333.33	10	56	3	476.19	10
20	6	666.67	10	56	6	238.10	10
20	12	333.33	10	56	12	119.05	10
20	24	166.67	10	56	24	59.52	10
20	48	83.33	10	60	3	444.44	10
20	96	41.67	10	60	6	222.22	10
24	3	1111.11	10	60	12	111.11	10
24	6	555.56	10	60	24	55.56	10
24	12	277.78	10	64	3	416.67	10
24	24	138.89	10	64	6	208.33	10
24	48	69.44	10	64	12	104.17	10
28	3	952.38	10	64	24	52.08	10
28	6	476.19	10	68	3	392.16	10

Table 4. The possible combinations of the variables N the number of modules in one direction, H height, L length, for Pavilions of total volume 800 000 m^3.

N	*H* (m)	*L* (m)	*W* (m)	*N*	*H* (m)	*L* (m)	*W* (m)
1	3	6676.666	10	32	3	18.021	5
4	3	426.667	10	36	3	15.288	5
8	3	114.167	10	40	3	13.333	5
12	3	56.296	10	44	3	11.887	5
16	3	36.042	10	48	3	10.787	5
20	3	26.667	10	1	6	6671.666	5
24	3	21.574	10	4	6	421.667	5
1	6	3343.333	10	8	6	109.167	5
4	6	218.333	10	12	6	51.296	5
8	6	62.083	10	16	6	31.042	5
12	6	33.148	10	20	6	21.667	5
16	6	23.021	10	24	6	16.574	5
1	12	1676.667	10	28	6	13.503	5
4	12	114.167	10	32	6	11.510	5
8	12	36.042	10	1	12	3338.333	5
1	24	843.333	10	4	12	213.333	5
4	24	62.083	10	8	12	57.083	5
1	48	426.667	10	12	12	28.148	5
4	48	36.042	10	16	12	18.021	5
1	96	218.333	10	20	12	13.333	5
1	192	114.167	10	1	24	1671.667	5
1	3	13338.333	5	4	24	109.167	5
4	3	838.333	5	8	24	31.042	5
8	3	213.333	5	12	24	16.574	5
12	3	97.593	5	1	48	838.333	5
16	3	57.083	5	4	48	57.083	5
20	3	38.333	5	1	96	421.667	5
14	3	28.148	5	1	192	213.333	5
28	3	22.007	5	1	3	4459.444	15

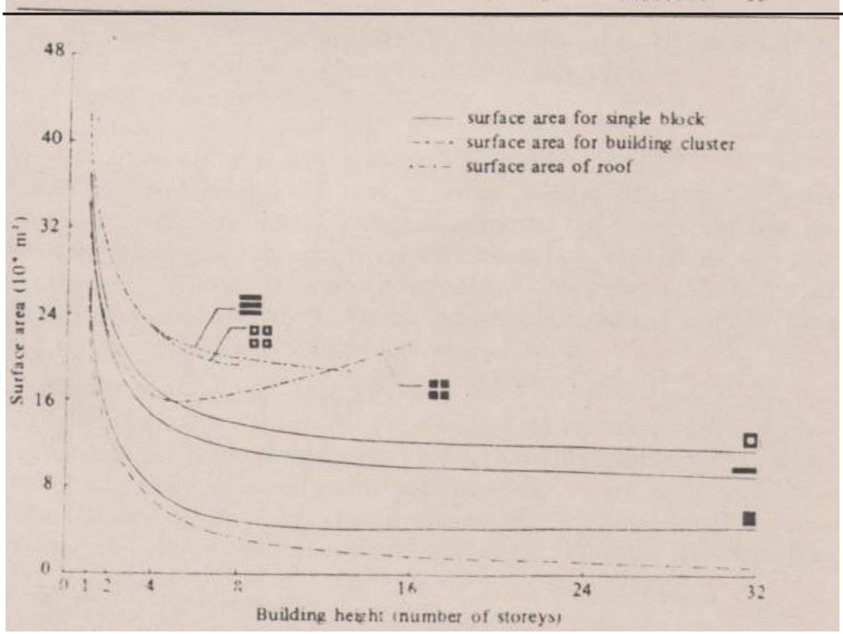

Figure 4. Total surface area of building of volume 800000 m^3, with respect to building height for single and multiple building blocks of Pavilion, Street, and Court type of built forms (represented by their ground plans)

The situation is very different for larger values of N, and it can be seen that the surface area of the Pavilion forms increases with increasing building height beyond four storeys. For buildings taller than four storeys, the surface area of the Street and Court does not change much with changes in height. The built form of Jaisalmer cannot be characterised by any of the three basic forms. The simplest way of describing this form is to think of it as a series of Courts forming an overall layout of Streets (figure 5). The surface area of the walls of this type of built form is less than that of Courts alone.

The solar radiation interception properties of these building forms can now be studied to determine their relative efficiencies.

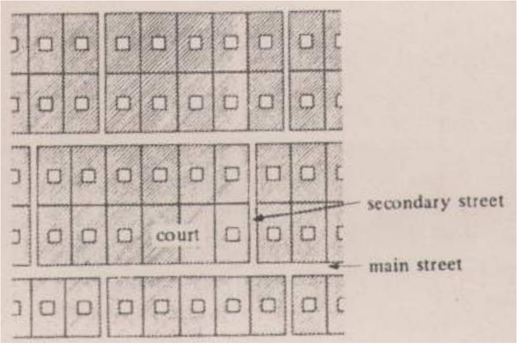

Figure 5. Schematic plan of the central area of Jaisalmer.

Solar radiation analysis

For design purposes, the solar radiation incident on an isolated single building can be determined from available tables (Seshadari et al. 1969; Mani. 1980) which provide hourly or total daily solar heat flux incident on differently oriented surfaces for various values of solar declination and latitude. This method cannot be applied to building clusters because of the shadowing of one block by another. For Court forms, the problem is further complicated by the self-shading of the courtyard walls.

The incident solar radiation can be divided into three parts:

1. direct or beam radiation.
2. diffuse radiation.
3. reflected radiation (from ground and other buildings).

The relative and absolute values of these three components (Sayigh, 1979) depend upon various geographic, climatic, and environmental factors, on the one hand. and upon certain physical characteristics (like orientation. reflectivity of surfaces. separation between building blocks) of the building configuration on the other hand A detailed discussion of all these different factors is beyond the scope of the present work but certain observations about them are necessary.

Direct or beam radiation

The theory for ascertaining the direction and intensity of beam radiation is well developed and, of the three components of solar radiation, this is of primary importance particularly in warm regions with clear sky conditions (typical of a desert area). The direction of the bean) radiation is given by the altitude (α) and azimuth (θ) angles. These two angles can be determined from the following relationships:

$$\text{Sin}\ \alpha = \cos\lambda \cos\delta \cos\Omega + \sin\lambda \sin\delta \quad (1)$$

$$\text{Sin}\theta = \cos\delta \sin\Omega / \cos\alpha \quad (2)$$

and

$\cos\theta = (\sin\delta - \sin\lambda \sin\alpha) / \cos\lambda \cos\alpha$ (3)

where

λ is latitude,

δ is solar declination: positive for north, negative for south,

Ω is hour angle: positive in the morning, negative in the afternoon.

The intensity of beam radiation also changes with the altitude of the sun, the altitude of the observer above mean sea level and the turbidity of the atmosphere. Rao and Seshadari (1961) have given the following simplified relationship between the altitude of the sun and the intensity of beam radiation for the standard Indian atmosphere.

$I_{DN} / I_O = 0.921 / (1 + 0.3135 \operatorname{cosec}\alpha)$, (4)

where

I_O is the intensity of solar radiation outside the earth's atmosphere,

I_{DN} is the intensity of beam radiation near the earth's surface.

Diffuse radiation

The intensity of diffuse radiation depends upon atmospheric conditions, the most important of which is the presence of' dust particles or water vapour which cause scattering of the beam radiation. The presence of clouds in the sky can radically change the intensity and direction of diffuse radiation and therefore it is not at all easy to estimate. Perhaps the simplest estimate of the direction of diffuse radiation is to assume that it is isotropic over the hemispherical sky-dome. Measured values of solar radiation on a horizontal surface in Delhi indicate that about 30% of the total radiation is diffuse (Mani, 1980). Thus,

$I_{TH} = I_{DH} + I_{dH} = (1+0.43)\, I_{DH}$, when $I_{dH} = 0.3\, I_{TH}$

$= 1.43\, I_{DN} \sin\alpha$

where

I_{TH} is the intensity of direct and diffuse radiation on a horizontal surface,

I_{DH} is the intensity of direct radiation on a horizontal surface,

I_{dH} is the intensity of diffuse radiation on a horizontal surface.

Reflected radiation

Of the three components of solar radiation, the reflected component is the most variable and difficult to estimate. Its value for vertical surfaces can be up to 10% of the intensity of global radiation. This value is influenced only by the conditions of surrounding environment (such as the colour, texture, and distance of vertical surfaces and ground and not by the atmospheric conditions. It is not surprising therefore that no attempt has been made to estimate this component directly

Total radiation

When buildings are placed near one another, a part of the sky (presumably emitting diffuse radiation) is obscured from the reference vertical surface, reducing the intensity of diffuse radiation on that surface. However, it is likely that this reduction of diffuse radiation is made up by increased reflected radiation from the ground and from other vertical surfaces nearby. Thus, it is not grossly inaccurate, for the purpose of this exercise, to assume that the intensity of diffuse radiation on walls is independent of the separation building blocks and may be derived from equation (5)
which gives the diffuse radiation on horizontal surfaces. The total radiation is then

given as follows:

$I_{TH} = 1.43\ I_{DN} \sin\alpha$ (5)

$I_{TV} = ½\ (0.43\ I_{DN} \sin\alpha) + I_{DN} \cos \Phi$ (6)

where

I_{TV} is the intensity of total radiation on a vertical surface,

Φ is the angle of incidence of beam radiation on the surface.

The first part of equation (6) is the diffuse component and the second part is the direct component.

To obtain an estimate of the total incident radiation for a building cluster, it is therefore necessary to determine angle Φ for each of the vertical surfaces and to calculate the area on which beam radiation is incident. The angle Φ and ITV can be calculated from equations (1) and (4), respectively ($\cos\Phi = \cos\alpha \times \cos\Upsilon$, where Υ is the wall solar azimuth).

Mutual shading of buildings

The thermal properties of a cluster of buildings can be determined by analysing a single building in the cluster, but this is not possible with solar radiation analysis because of the shading of' one building by another. Figure 6 shows a typical cluster of Courts. with the shading pattern for a particular combination of solar azimuth and altitude. The exact boundary of the shaded part of each building changes continuously from sunrise to sunset. The normal graphic methods of shadow projection used by architects are too tedious to be used for this analysis. Knowles (1974) has used an elegant photographic technique for shading analysis of very complex forms. A scale model of the building is constructed and put on a heliodon. The model is then rotated and photographed in such a way that the camera sees the model as the sun would see it. The total area of the building in the photograph, then represents the projected area of the parts of the building which are exposed to the sun I figure 7). The advantage of this technique is that very complex forms can be easily handled. because the angle of incidence of solar radiation on individual surfaces need not be calculated separately. The projected area obtained from the photograph is automatically corrected by the factor cos Φ for vertical surfaces and by sin α for horizontal surfaces. This technique is most useful for a detailed study of a complex form, but it becomes difficult to use for studying a large number of simpler forms.

Another technique that is becoming increasingly popular (Arumi, 1979) involves the use of a computer with graphic display and printout facilities. The computer

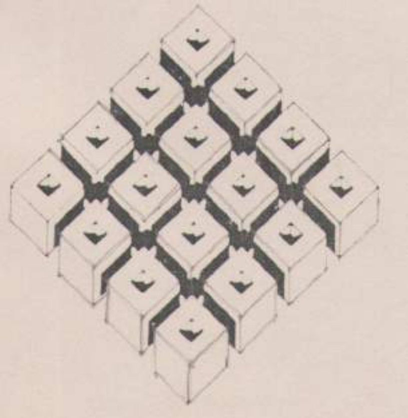

Figure 6. Shade and light pattern of a cluster of Courts

produces images of the building (as seen by the sun) after suitable rotations along two axes. The projected area of the building form can then be calculated from the printout or, in the case of interactive systems, it can be calculated by the computer itself. Unfortunately, the hardware and software for this kind of work are not available at present in Delhi.

A different technique is therefore required to evaluate the shading pattern of a large number of simple building forms. The technique chosen involves the use of a microcomputer without graphic facilities. Essentially, the technique consists of rotating the mathematical image of the building, in the same way that Knowles did, and obtaining modified images from which the solar-exposed projected area can be calculated by geometrical analysis. With a suitable program, the computer can give this area directly for hourly intervals and daily totals. For the Pavilion and Court building forms, the geometrical analysis can be greatly simplified and the shading pattern of large clusters predicted by the shading pattern of a 2 x 2 cluster of blocks. Figure 8 shows a generalised solar view of a 2 x 2 cluster of cube blocks. Block A is shaded by blocks B, C, and D. Blocks B and C are shaded only by block D on the right and left, respectively. Block D is not shaded at all. Blocks A, B, C, and D can represent all the blocks in a larger cluster. By further analysis of the figure it can easily be seen that the exposed area of blocks A is given by the parallelogram 1 2 3 4, and the shaded area of blocks B and C is given by the parallelograms 5 6 7 8 and 9 10 1 1 12. The total solar-exposed area of each block can be easily calculated. It can be seen that the shaded area of block A depends upon the street width (w) and

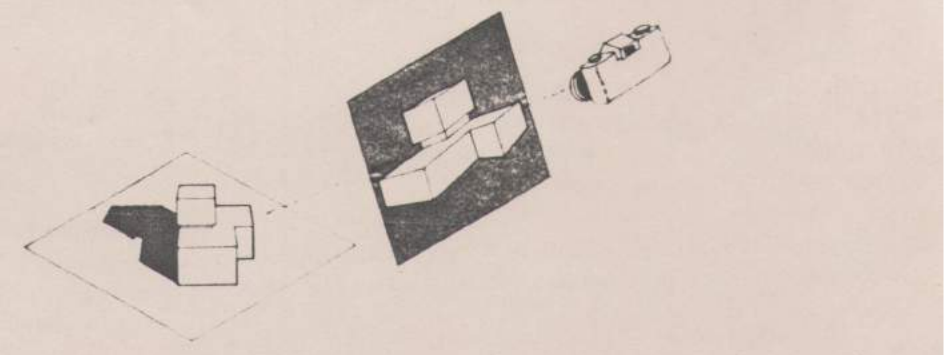

Figure 7. Photographic method of calculating the sunlit area of a complex building form

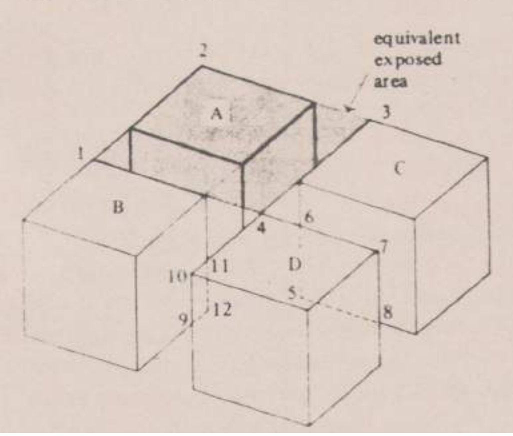

Figure 8. Solar view of a 2 x 2 cube cluster

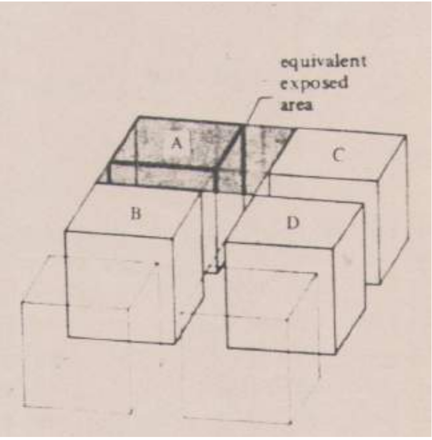

Figure 9. Solar view of a 2 x 2 cube cluster for a low solar altitude

height (H) of the blocks. For a given H/w ratio, the percentage of shaded wall-area remains constant for any size of block. Thus, the shading of walls (there is no shading of roofs with blocks of equal height) depends only upon the dimensions of the street and is independent of the length and width of the blocks.

During the course of a day, other different situations can also arise, but in each case the same analysis can give the solar-exposed area. A slight inaccuracy arises in case of figure 9, where the area 1 2 3 4 is somewhat less than the solar-exposed area of block A. This is not a serious error, as the situation arises only with low- solar altitudes when the 'solar exposure' (see later) is small. In the case of Courts, a deduction is necessary for the floor area of the courtyard defined by the parallelogram 1 2 3 4 in figure 10 which can be easily computed.

For the Street type of blocks, no separate analysis is necessary because there are only two possible situations: (1) when one side is shaded and (2) when no shading takes place (figure 1 1).

With this analysis it is possible to develop a computer program that can give the solar-exposed area for any of the three building types, for any given latitude, solar declination, and time of day.

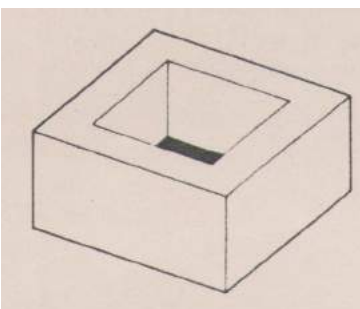

Figure 10. Solar view of a Court

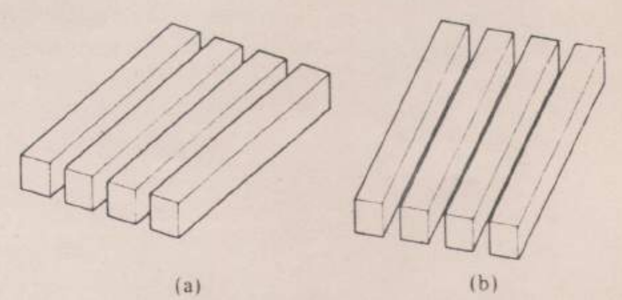

Figure 11. Solar view of a Street (a) one side shaded, (b) no shading

Solar exposure

It is convenient to express the incident direct solar flux, SD, for a given combination of variables (building-cluster dimensions. latitude. declination. and hour angle) as follows:

$$S_D = IA_{SD}. \qquad (7)$$

where

I is the solar constant

A_{SD} is the effective solar-exposed area for beam radiation, given by

$$A_{SD} = A_S \, I_{DN} / I_{ON} , \qquad (8)$$

where

A_S is the projected area of the solar-exposed parts of the building cluster, as calculated above.

I_{DN} / I_{on} is the attenuation factor for solar radiation.

The area ASD is calculated for mid-hours from sunset to sunrise, and the sun of all values of ASD for a given day then becomes a measure of the amount of direct solar radiation that the particular building form is likely to receive. This includes the effect of the angle of incidence of beam radiation, the intensity of beam radiation, and the shading of building surfaces by one another.

The total diffuse radiation incident on the building is similarly computed:

$$S_D = IA_{Sd}, \quad (9)$$

where,

ASd is the effective area of the building for diffuse radiation, Sd is the total diffuse Solar flux incident on the building.

The total solar flux, S, is then given by

$$S= S_D+ S_d= I(A_{SD}+A_{Sd})= IS_E. \quad (10)$$

The term S_E, which has units of area, will be called 'solar exposure' and will be used to compare the solar properties of different building forms.

Knowles has used a similar term, E_i, as a measure of the insolation properties of Buildings, but it is an inaccurate measure as it does not include the effect of diffuse radiation and even for beam radiation the variation of intensity is taken as a sine function of the solar altitude which is true only for radiation intensity on a horizontal surface. The effect or assuming that I_{DN}=I sin α is to minimise the differences in radiation received at low solar altitudes and thus to eliminate the effect of solar radiation on vertical surfaces. The difference between the two factors sin α and 0.921/(1 +0.3135 cosec α) used in equation (4) is shown in figure 12. The solar exposure for a cube on a summer and on a winter day is shown in figure 13.

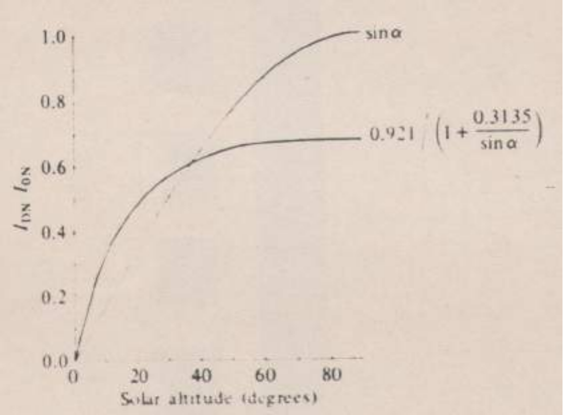

Figure 12. Comparison of two expressions for the attenuation factor, I_{DN}/I_{0N} , for solar radiation, with respect to solar altitude

Efficiency of building form

For obvious reasons. larger buildings have a larger solar exposure than do smaller buildings. To study the relative efficiency of different building forms, of different sizes perhaps. It is desirable to have a nondimensional characteristic which gives an indication of their solar properties. For those regions where winter heating is a necessity the insolation of a building form can be measured by comparing the winter solar exposure with summer solar exposure (Olgyay, 1963: Knowles. 1974). But in other areas. where winter heating is not a problem. efficiency has to be measured by minimising summer solar exposure. which depends upon the reference building floor area land. therefore. on volume). To arrive at an index similar to the one for winter performance, one needs a building shape that has the least solar exposure. Since one is dealing with floor areas, one obvious choice is to compare the solar exposure of the given building form with the solar exposure of the equivalent floor area on the ground without building.

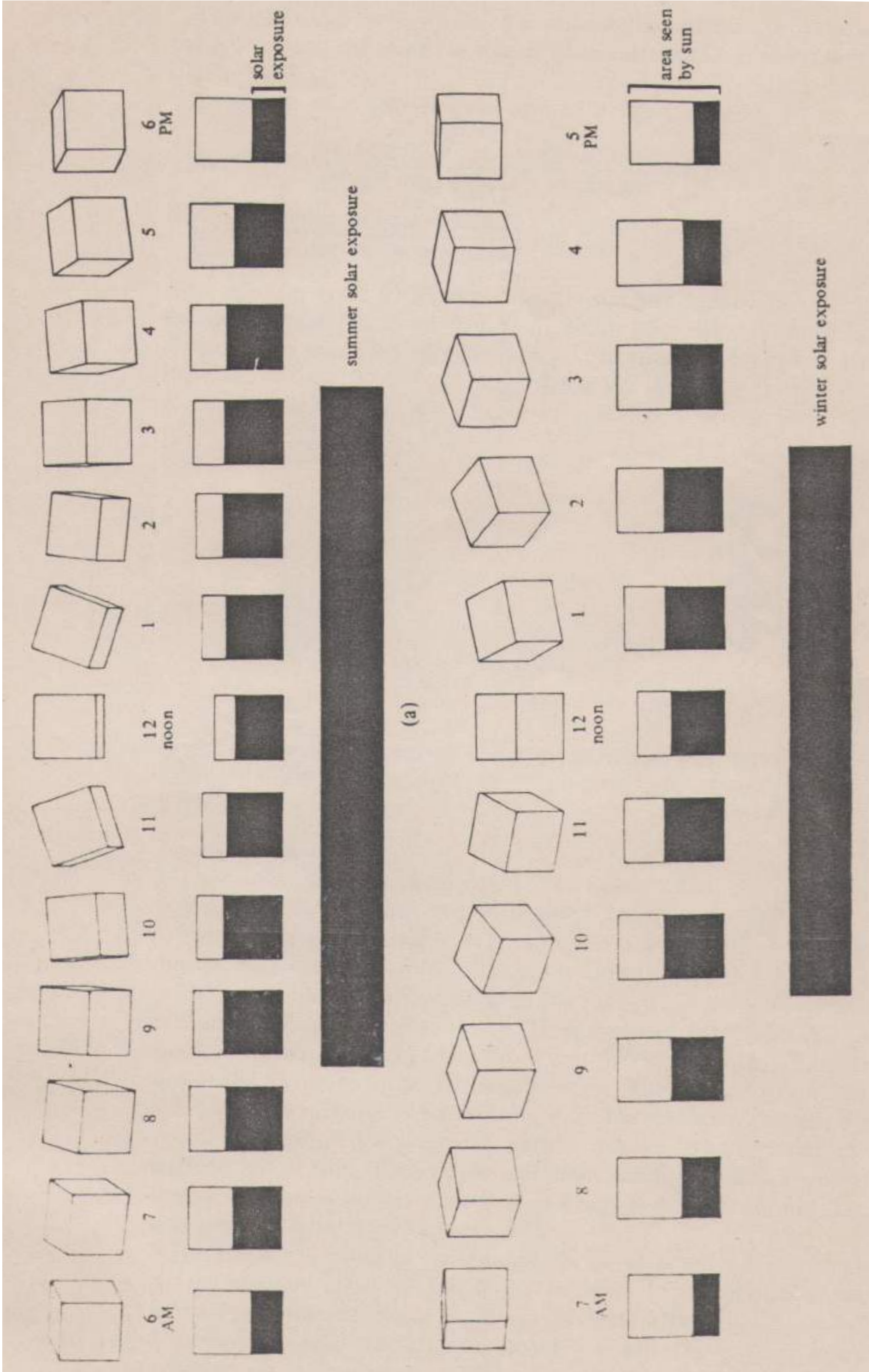

Figure 13 Hourly solar views, projected area and solar exposure and total daily exposure for a cube for (a) summer, and (b) winter (for 29°N latitude).

This index can be viewed as the comparative solar exposure of a given floor area on the ground and the same floor area when distributed in a certain way in a building (figure 14).
Two kinds of efficiencies can now be defined:
E_S= (1-(building solar exposure in summer)/(ground solar exposure in summer))100%

E_W= ((winter solar exposure)/(summer solar exposure))100%
E_S is valid for areas with predominantly summer conditions. The possible range of E_w extends beyond 100% and that of E_S below 0%. The efficiency factors E_S and E_w are not to be confused with the normal quantitative concept of efficiency in which the range is from 0 to 100% only. These are mere qualitative indicators used for comparing the relative performance of buildings.

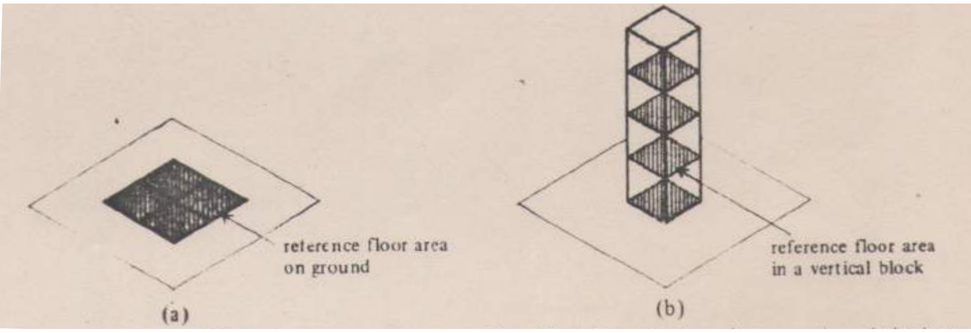

Figure 14. Two different ways of arranging a given floor area: (a) on the ground and (b) in a four-storey building. The summer efficiency is given by the ratio of solar exposure for the two configurations.

Results and discussion

It is generally accepted (Knowles. 1974: Evans. 1980) that a high surface-to-volume ratio renders the building more susceptible to environmental stress, resulting in a poorer thermal performance. Although this is quite true of buildings in a cold climate. it is not necessarily so for a hot climate.

The change in the surface area for the reference volume (800 000 m^3) with respect To change in building height for the three types of forms was shown in figure 4. It can be seen that for N =1 the Court and Street forms have a larger surface area than that of the Pavilion, for all building heights. The surface area of all the forms decreases with Increase building height. The situation changes when the reference volume is distributed in a large number of blocks. The surface area of Pavilion forms decreases up to four storeys in height after which it increases, and after twelve it becomes greater than that of Court and Street forms. The four-storey height thus critical for further study.

The effect of change of building height on solar exposure of single building blocks and the resulting efficiencies is shown in figure 15. Efficiency E_S (a measure of building performance in hot climates) increases with building height for all three types of forms. It seen that after eight-storey height, the increase is negligible, but it is a maximum up to four-storey height. The maximum efficiency is obtained by the Pavilion form. Efficiency Ew (a measure of building performance in temperate climates does not increase so dramatically with increasing height, but for the Street And Pavilion forms the increase continuous. The efficient form is the Street, for which the efficiency is greater than 100% after about twelve storeys.

The efficiency of the Court is higher than that of the Pavilion but much less than that of the Street. In the case of building clusters (figure 16) there is a marginal difference between Ew for Street and Court for building height up to four storeys; but for taller buildings the Street is definitely more efficient than the Court and the Pavilion.
The choice of building form for a temperate climate is thus clear. The Street is the most efficient building form for such climates. For warm climates, the situation

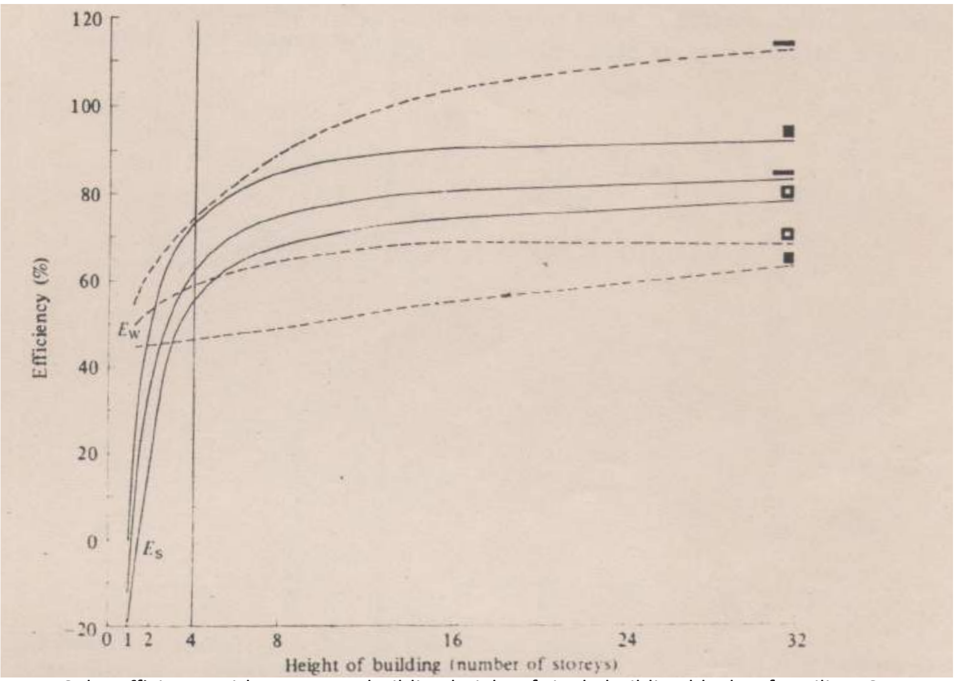

Figure 15. Solar efficiency with respect to building height of single building blocks of Pavilion, Street, and Court types (represented by their ground plans) .

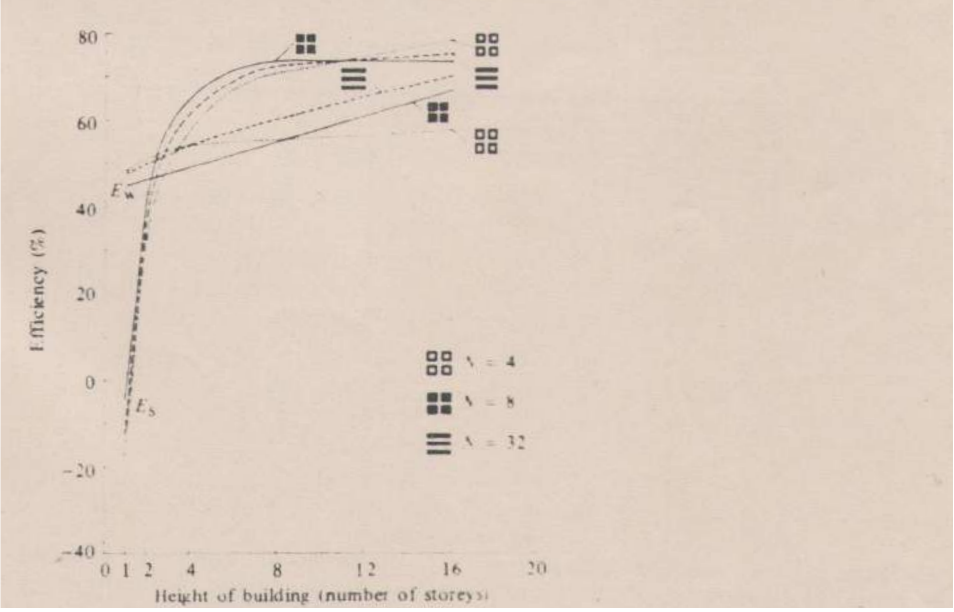

Figure 16. Solar efficiency with respect to building height of building clusters of Pavilion, Street, and Court types (represented by their ground plans) . N is the number of modules in one direction

is somewhat more complicated. The Pavilion has the highest efficiency up to eleven storeys after which the Court becomes more efficient. ES for the Street always lies between ES for the Court and Pavilion. A further analysis of these three building forms is necessary to account for changes in street width and degree of subdivision.

Street width and subdivision

Figures 17, 18, and 19 show the effect of subdivision of the reference volume and street width on efficiency for building heights of one, two, and four storeys.

For Pavilions (figure 17), the Es efficiency is reduced as the number of subdivisions is increased. This drop in efficiency is partially made up by a narrower width of street.

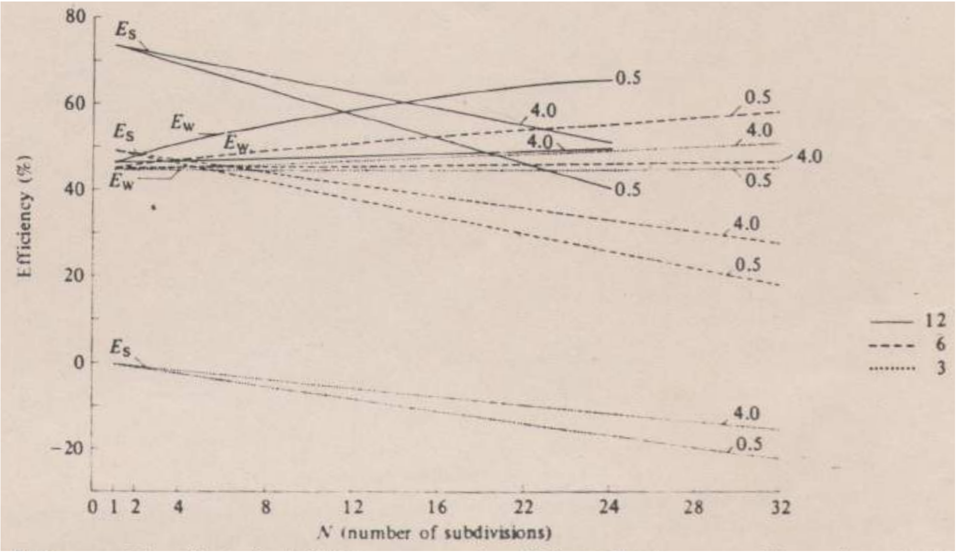

Figure 17. The effect of subdivision (N) on solar efficiency for Pavilions. The numbers on the lines are values of H/w, the ratio of building height to street width. The building height (m) is given in the key

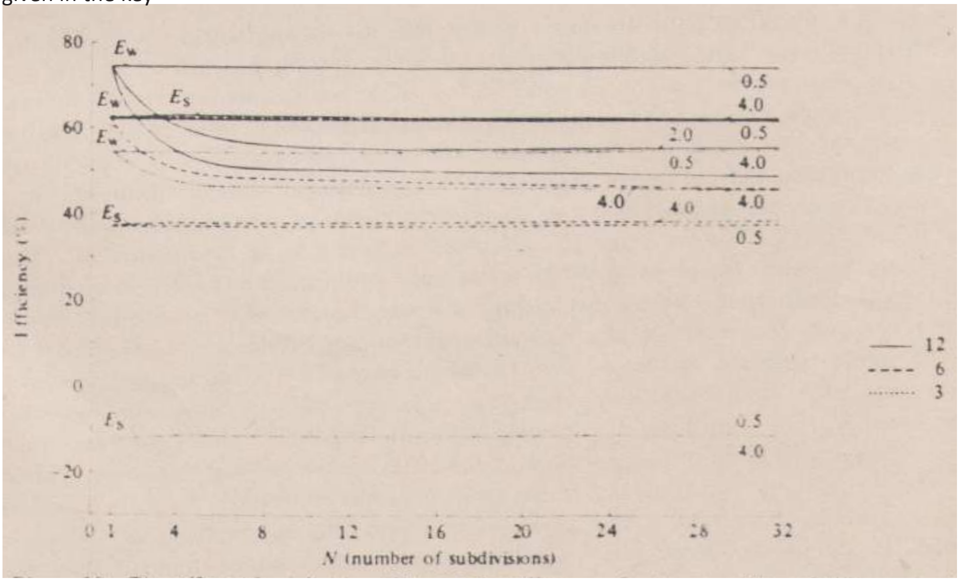

Figure 18. The effect of subdivision (N) on solar efficiency for Streets. The numbers on the lines are values of H/w, the ratio of building height to street width. The building height (m) is given in the key

On the other hand, the E_w efficiency increases with larger number of blocks. For Street-type buildings (figure 18), E_s is not affected by either change of street width or by the number of subdivisions. However, there is a marked decrease in the E_w efficiency with decrease in street width, particularly for four-storey height. The Court (figure 19) exhibits unique characteristics as E_s increases with greater subdivision of reference volume and with narrower street widths. For the Court, E_w is reduced as Street width is decreased.

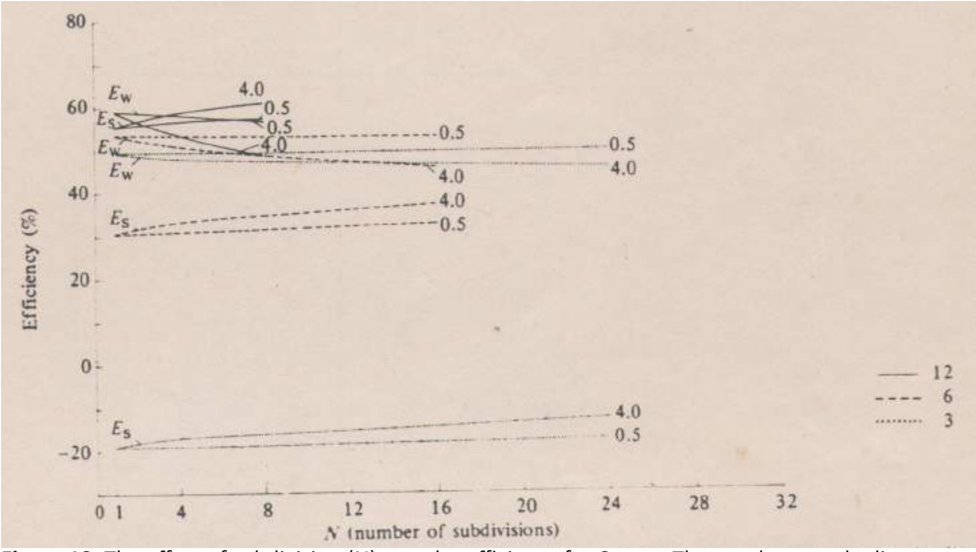

Figure 19. The effect of subdivision (N) on solar efficiency for Courts. The numbers on the lines are values of H/w, the ratio of building height to street width. The building height (m) is given in the key

Orientation

In all the above calculations, the building clusters were oriented to face in a north-south direction. But it is possible that efficiency of building forms varies with the orientation of the facades. Figures 20 and 21 show ES and Ew, respectively, in relation to orientation. The conventional orientation of the long axis along the east-west direction is represented by the building azimuth of 0O and the long axis along the north-south direction is taken as the 90O building azimuth. The wisdom of the conventional orientation of major facades facing in a north—south direction is borne out by the for a Single Street in figure 20. Ew varies from 47.5% for the 90O azimuth to for the 0O azimuth. But some of the other forms show completely different properties. The single Pavilion is hardly affected by orientation changes. and the Single Court achieves equally high efficiencies at 30O intervals. But it is more fruitful to exam me the efficiency of multiple forms, as a single building of 800000 m3 is unrealistic. The peak efficiency EW of multiple Streets is the same as that of multiple Pavilions, whereas the peak efficiency of multiple Courts is lower and the Jaisalmer form has the lowest efficiency. It can be seen that in all cases the efficiency at the 0O azimuth is the same as at the 90O azimuth.

The relative efficiency of different forms (figure 21) is totally changed for ES. The single Pavilion is most efficient, and the single Street and Court are less efficient. Amongst the multiple forms, the ES of Jaisalmer type form is the highest and it is not affected by orientation. The efficiency of multiple Courts is similar to that of multiple Streets. Surprisingly, the ES of multiple Streets is the same with east-west or north-south orientation. This is because of the mutual shading of buildings which is almost 0 at the 0O azimuth, is maximum at the 90O azimuth. If the street width is decreased (that is H/w is increased beyond 2), the efficiency at the 90O azimuth will be even higher than at the 0O azimuth.

Since the effectiveness of structural shading devices commonly used in buildings is a maximum on the north and south facades and much less on east and west facades,

it is possible that, when the relevant shading factors are taken into account, the simple efficiencies given in figure 20 and 21 will change.

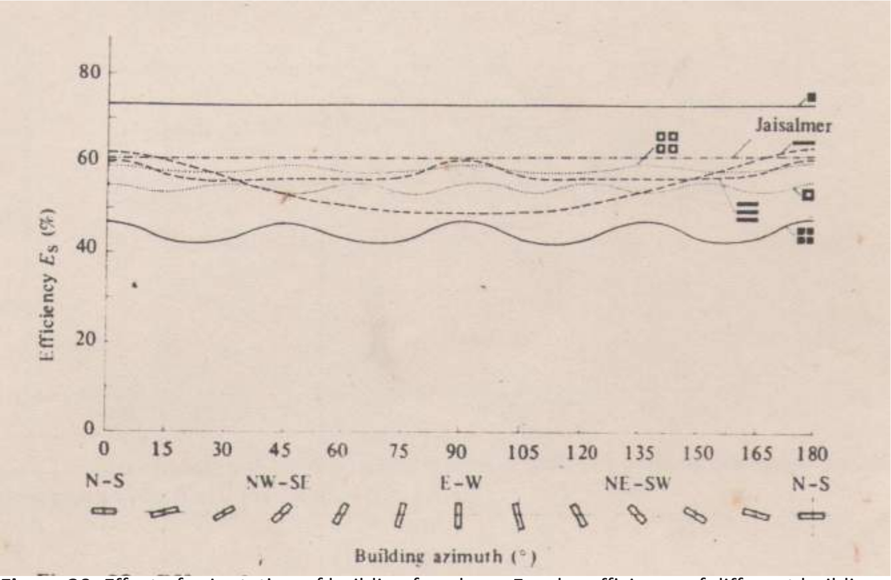

Figure 20. Effect of orientation of building facade on E_s solar efficiency of different building configurations (represented by their ground plans) and for Jaisalmer.

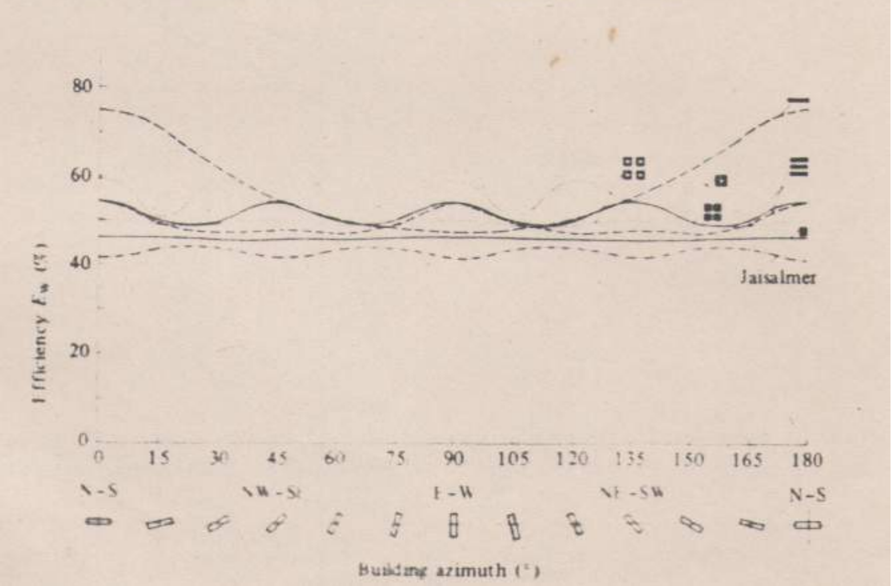

Figure 21. Effect of orientation of building facade on E_w solar efficiency of different building configurations (represented by their ground plans) and for Jaisalmer.

Latitude

The efficiency of building forms for different latitudes is shown in figures 22 and 23. For warm climates the efficiency E_s (figure 22) of all forms is nearly independent of latitude and almost identical efficiency is achieved by the Street (single or multiple), the multiple Court, and the Jaisalmer-type forms. The E_w efficiency (figure 23) of all forms shows a drop with the increase of latitude, and at all latitudes the single Street gives the highest efficiency, followed by the single Court. For multiple forms, E_w is nearly the same for Streets and Pavilions.

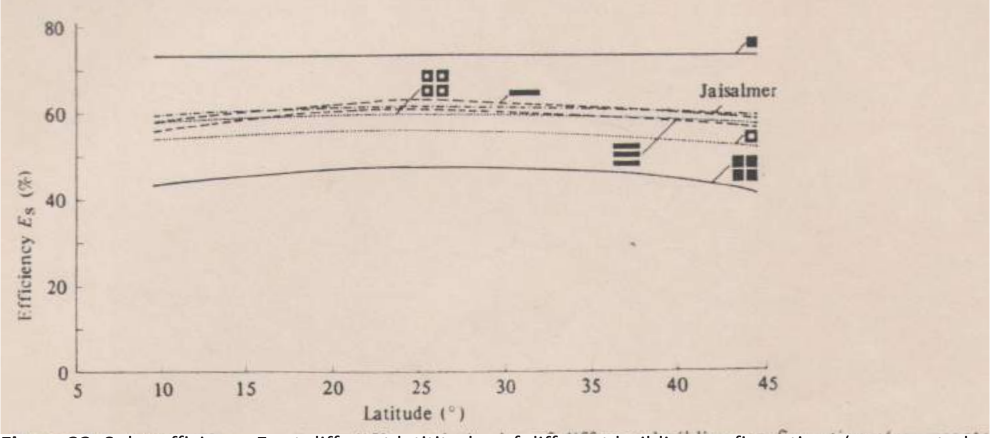

Figure 22. Solar efficiency Es at different latititudes of different building configurations (represented by their ground plans) and for Jaisalmer.

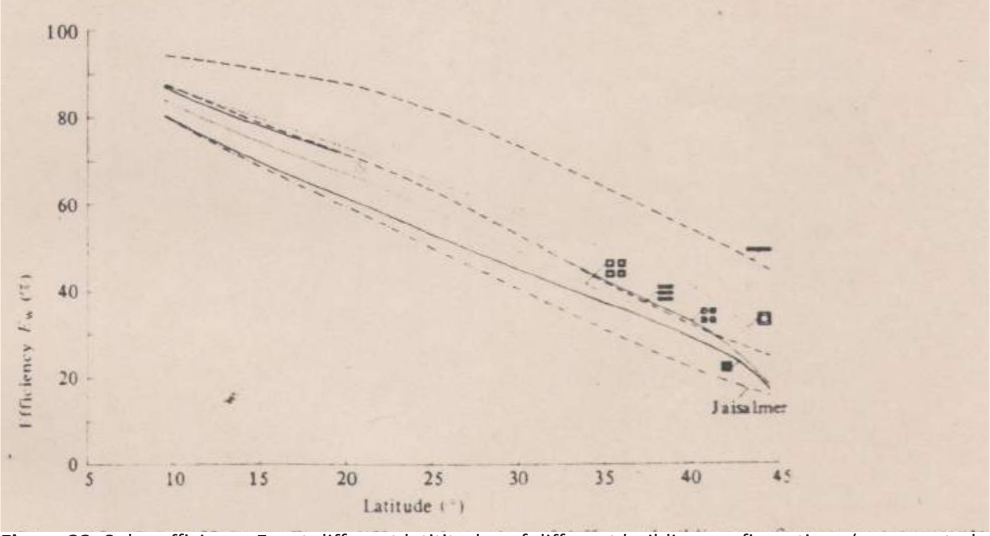

Figure 23. Solar efficiency Ew at different latititudes of different building configurations (represented by their ground plans) and for Jaisalmer.

Conclusions

The following conclusions may be drawn from the above analysis and discussion:

Warm climates

1. The choice of building form lies between the multiple Court and Street. Pavilion-type building gives rise to low solar efficiency.
2. Orientation of building is important for the single Street type, for which the long axis should be along the east—west direction. Courts can be oriented any direction. Multiple Streets can have east-west or north-south orientation with equal efficiency.

3. The width of streets running east-west is unimportant from a solar efficiency viewpoint, but streets running north -south should be as narrow as possible.
4. Unless special measures are adopted to shade the roof, buildings should not be less than four floors high.
5. For Courts, a large number of blocks with smaller courtyards are preferable to fewer blocks with large courtyards.
6. The Jaisalmer-type of planning is very efficient for reducing solar heat gain.

Composite climates
1 The ideal form for best Ew efficiency is the Street type.
2 Depending upon the latitude, the distance between buildings should be carefully chosen to eliminate shading in winter. For 29O (north or south) latitude a street width twice the height of buildings ensures the condition of no shading.
3 The orientation of Streets must be along the east—west direction. Any deviation from this leads to lower efficiency. For Courts, the orientation does not matter.
4 For both Courts and Streets, greater subdivision does not affect solar efficiency, but for Pavilions subdivision is not desirable.
5 The Jaisalmer type of plan is not suitable.

References
Arumi F N, 1979, "Computer-aided energy design for buildings" in Energy Conservation Through Building Design Ed. D Watson (McGraw-Hill, New York) pp 141 -160
Evans M, 1980 *Housing, Climate and Comfort* (Architectural Press. London)
Gupta V K, 1981, "Natural cooling of buildings" RR-SI, Innovative Informations Inc., Greenbelt, MD
Harkness E L, Mehta M L, 1978 *Solar Radiation Control in Buildings* (Applied Science Publishers, Barking,- Essex)
Hawkes D U. _1 981, "Building shape and energy use" in *The Architecture of Energy* Eds D U Hawkes, J Owers (Construction Press, Harlow, Essex) pp 7-21
Knowles R L, 1974 *Energy and Form*: *An Ecological Approach to Urban Growth* (MIT Press, Cambridge, MA)
Mani A, 1980 *Handbook of Solar Radiation: Data for India 1980* (Allied Publishers, New Delhi)
Markus T A, Morris E N, 1980 *Buildings, Climate and Energy* (Pitman, London)
Martin L, March L (Eds), 1972, "Speculation 4 (1966)" in *Urban Space and Structures* (Cambridge University Press, Cambridge) pp 35-38
Olgyay V, 1963 *Design with Climate* (Princeton University Press, Princeton, NJ)
Peach J, 1981 , "Energy target for buildings" in *Experience of Energy Conservation in Buildings* Ed. A F C Sheratt (Construction Press, Harlow, Essex) pp 10-26
Rao K R, Seshadari T N, 1961, "Solar insolation curves" *Indian Journal of Meteorology and Geophysics* 12 267-272
Sahu S, 1982, "Multi-storey building envelopes and solar heat gains" paper presented at the Asian Regional Conference on Tall Buildings and Urban Habitat, Kuala Lumpur; copy obtainable from author at Department of Architecture, University of Roorkee. Roorkee, UP, India
Sayigh A A M, 1979, "The solar radiation spectrum and its utilization" in *Solar Energy Application in Buildings* Ed. A A M Sayigh (Academic Press, New York) pp I -16
Seshadari T N, Rao K R, Sharma M R, Sarma G N, Ali S, 1969 *Climatological and Solar Data for India* (Sarita Prakashan, Meerut, India)