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Building Form and Environmental Performance: Archetypes, Analysis and an Arid Climate

keywords Bioclimatic design; Archetypal forms; Image-processing;
Vernacular architecture; Hot-arid climate

Building form and environmental performance: archetypes, analysis and an arid climate

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Abstract

Leslie Martin and others at Cambridge University addressed the question “What building forms make the best use of land?” in a number of influential papers published in the late 1960s. They selected six simplified urban arrays based on archetypal building forms. Then they analysed and compared the archetypes in terms of built potential and day lighting criteria, eventually reaching the conclusion that courtyards perform best. Their results, which inspired a generation of designers, are briefly reviewed here and reassessed in environmental terms using innovative computer analysis techniques. Furthermore, the implications of their question, which to date has not addressed the link with climate, are explored using a case study in a hot-arid region.

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1. Introduction

“What building forms make the best use of land?” This million-dollar question for planners and architects was addressed in the late 1960s at the Centre for Land Use and Built Form Studies in Cambridge (now The Martin Centre for Architectural and Urban Studies) by Leslie Martin, Lionel March, Michael Trace and others. It led to a number of influential papers [1], which had an enduring influence on the practice of urban design. They inspired more recent work of Gupta [2,3], Blowers [4] and Steemers et al. [5]. Furthermore, following the recent death of Sir Leslie Martin, some of the original work has been reprinted and the focus of commentary [6].

This paper aims to extend the analysis of building form archetypes first launched by Martin and March. Their main findings are briefly reviewed and subsequently, reassessed in environmental and energy terms. Using innovative techniques for environmental urban analysis, based on image processing, offers an integrated approach to looking into the complexity of environmental behaviour of the urban context. This analysis is further extended by examining a real urban case study in the hot-arid climatic context and reveals some of the environmental processes associated with successful vernacular archetypes.

2. The research context

2.1. Original findings

The question posed above demands, of course, two clarifications: that of best land-use and that of building form. The definition of optimum land-use can be linked to quantifiable parameters, such as the built potential (ratio of the floor area of the built form to the site area) and the availability of daylight [7]. Concerning built form, Martin and March examined a number of simplified or archetypal forms; this choice allowed them to limit the complexities found in real urban textures and to examine and compare the impact of geometry alone, at a time when computer power was limited. Results could be more easily interpreted than if studying real urban textures. The choice and definition of these simplified archetypes became very popular in generic studies and were extensively adopted, as shown later in the paper.

Initial results focussed on two forms: courtyards and pavilions. Courts resemble the traditional building forms which are found in many countries (including Cambridge, UK; Figs. 1–10) pavilions reflect the more contemporary tower building forms, which became popular after the Modern Movement.

A comparison between an urban array of courtyard or pavilion archetypes is shown in Fig. 2, both with 50% site coverage, the same building height and floor area, as 49 pavilions or in the form of 25 courtyards. The first interesting

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Fig. 1. Courts are an archetypal urban form prevalent not only in hot-arid climates but also in cooler climates in cities, such as Cambridge, UK.

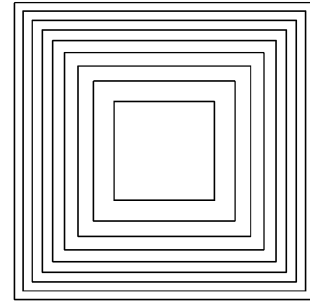


Fig. 3. Fresnel's diagram: all concentric squared annuluses have the same surface area, which is also equal to the area of the centre square.

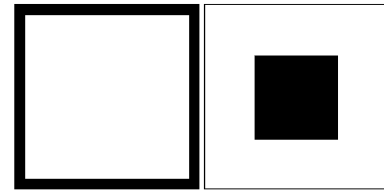


Fig. 4. Martin Centre logo, where the surface area of the black perimeter on the left (court archetype) is the same as the central square on the right (pavilion archetype).

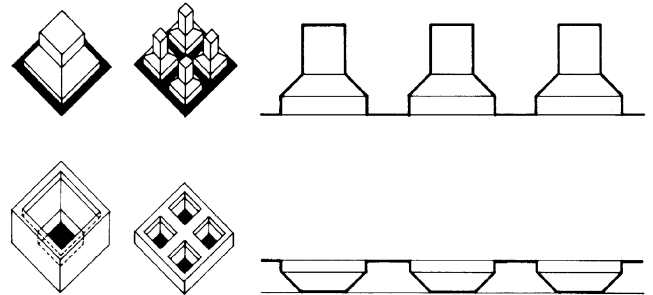


Fig. 5. Pavilions and courts in section and axonometric view [7].

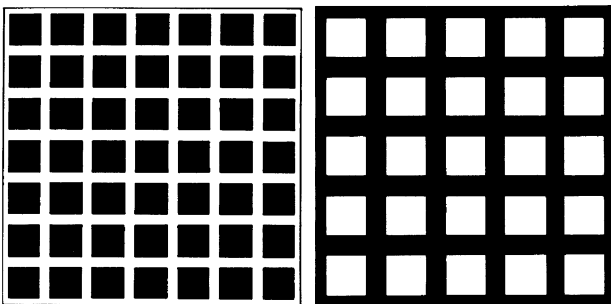


Fig. 2. Two archetypal urban patterns, based on pavilions and courts (black represents buildings) with the same site coverage, building height and total floor space [7].

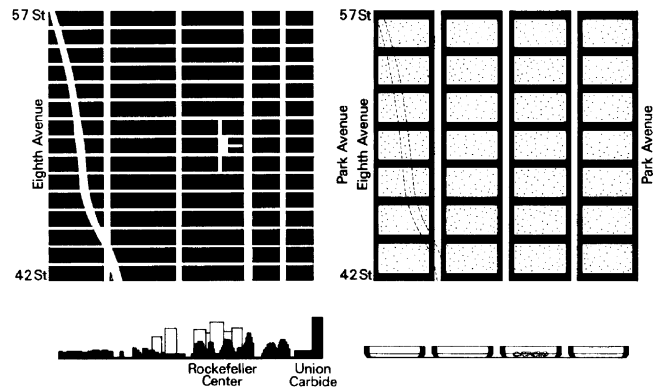


Fig. 6. Leslie Martin and Lionel March's (1972) radical proposal to replace a part of central Manhattan with large courts. This would have provided exactly the same amount of floor space while creating large open spaces and reducing the height of buildings from an average of 21 storeys to 7.

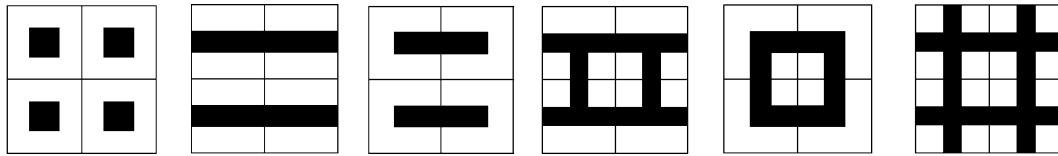


Fig. 7. Generic urban forms, based on Martin and March [7] and environmentally reviewed by Steemers et al. [5]. From left to right: pavilions, slabs, terraces, terrace-courts, pavilion-courts and courts.

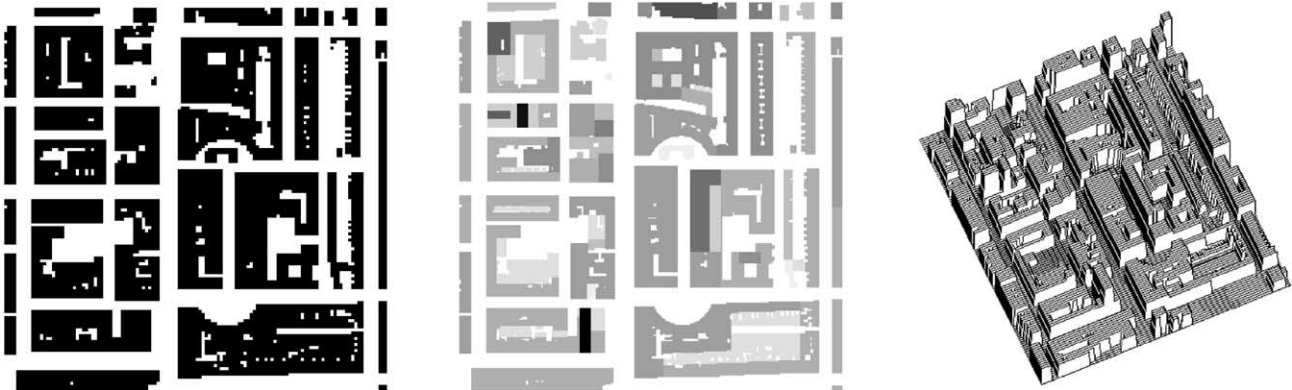


Fig. 8. Urban ground map showing built and unbuilt areas (left) and urban DEM (middle) and axonometric view (right) for a selected case-study in central London.

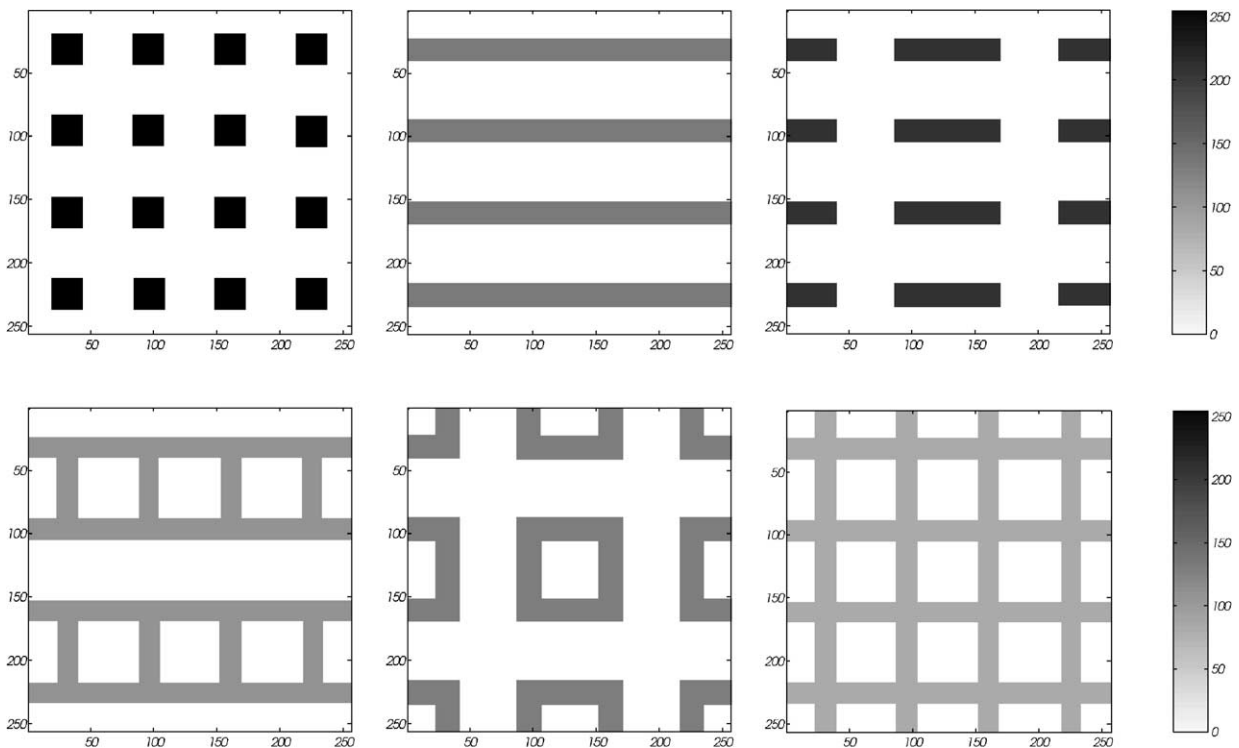


Fig. 9. DEMs of the generic urban forms shown in Fig. 7.

observation is how much more open space (white) there seems to be in the courtyard option. This is because open areas ‘clot’ together, instead of being dispersed around pavilions, which in environmental terms is a critical characteristic for courtyards, as will be discussed later.

Raymond Unwin, the direct successor of Ebenezer Howard and the Garden City tradition, observed that as population increases around the perimeter of a town, the commuting time (distance from the centre) is increased by less than the direct proportion to the increased population.

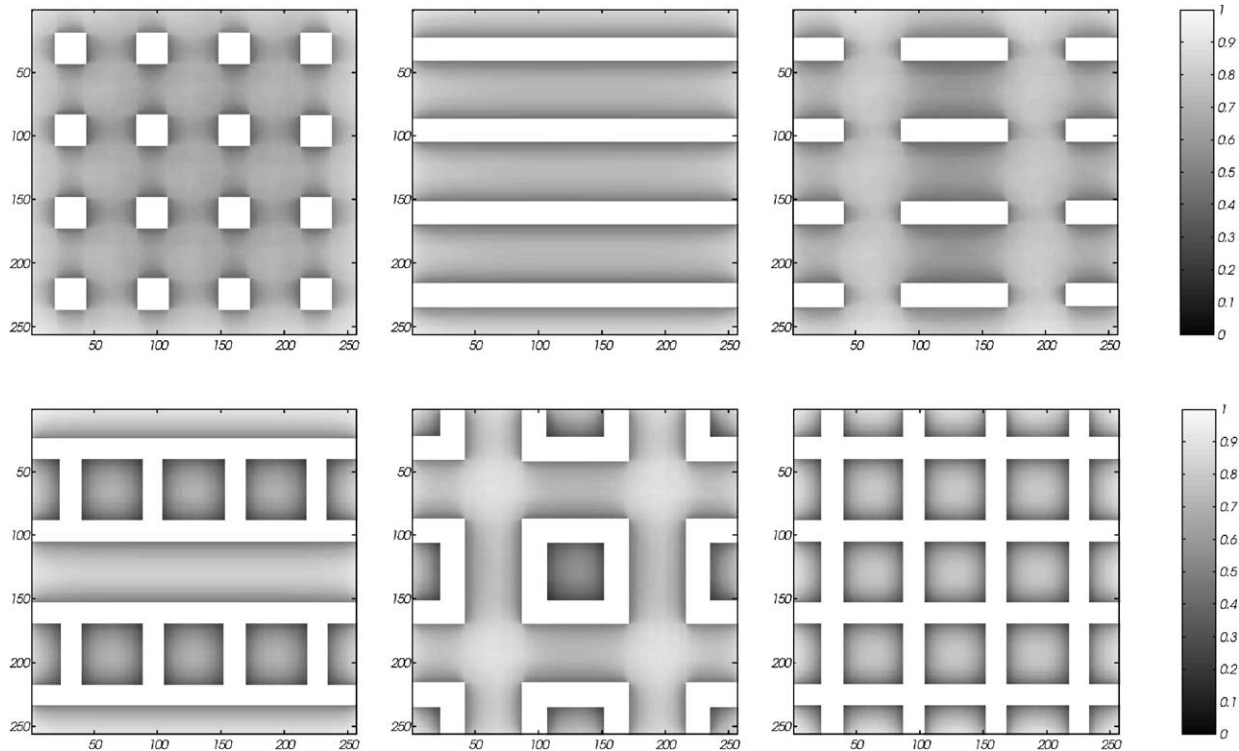


Fig. 10. Graphic presentation of sky view factors for the six generic urban forms.

The same concept on a square geometry is clearly graphically represented by the Fresnel diagram (Fig. 3) perhaps surprisingly each annulus (including the central square) has equal area. This diagram has extensively been adopted to make the point about the effectiveness of distributing built volume on the perimeter of a site, thus in a courtyard shape, as opposed to a centralised form as with pavilions. This concept is represented iconically in the logo of the Martin Centre (Fig. 4).

If the same kind of reasoning is extended in three dimensions, we can imagine a comparison between the two forms presented in Fig. 5, a pavilion and a courtyard (also called antiformal), each summing up to the same floor space and the same internal depth of room. As a result “the court form is seen to place the same amount of floor space on the same site area with the same condition of building depth and in approximately one-third the height required by the pavilion form” [7]. It is believed that prior to them, Le Corbusier had intuitively reached a similar conclusion in terms of land-use in the *Maisons Jaoul* (1954–1956) [8].

These studies eventually led to a provocative speculation to replace the centre of Manhattan with large courts, thus reducing the height of buildings from an average of 21 storeys to 7 (Fig. 6). A number of courtyard-type buildings were also designed by Leslie Martin and others, of which a famous example, is *Harvey Court*, a residential development for *Gonville and Caius College* in Cambridge.

A more extensive and accurate comparison between different “ways of placing buildings on the land”, however,

should take into account additional environmental parameters and possibly consider more simplified forms. In addition to the pavilion (a finite form) and the court (which extends infinitely along two axes), another elementary form can be considered: the street, which extends, potentially, infinitely along one axis. Some other combinations of these three basic forms can be sought, which generate the six archetypal forms presented in Fig. 7. These were examined by March and Trace [9] and compared not only in terms of their efficiency in built potential but also in terms of daylight availability. Results confirmed that land use performance improves with increasing circumference, i.e. courtyards perform better than pavilions.

2.2. Further developments

The adoption of Martin and March’s archetypal urban forms has been extensive during the last three decades in various kinds of researches, specifically those aiming at assessing aspects of the environmental behaviour of urban form. The attractiveness of these generic forms mainly lies in their simple and repeatable characteristics, thus eliminating the complexities found in real urban sites and allowing for a more systematic comparative analysis of geometry and built form.

For example, Gupta [2] was interested in evaluating thermal response of non-air-conditioned building forms in the context of a hot-dry climate. He employed three generic building forms—pavilion, street and pavilion-court—the

latter being representative of vernacular buildings. Built form ‘efficiency’ (measure of thermal performance in a certain climate) and solar exposure were analysed with respect to key form parameters, such as building height, street width and façade orientation. Gupta [3] went further in investigating the link between solar exposure per unit surface area of building and discomfort, with implications for heating and cooling energy consumption.

Stemers et al. [5] addressed the relationship between urban microclimate and form, identifying key environmental characteristics. Again employing Martin and March’s generic urban forms, comparative analysis allowed the objective isolation of specific morphological descriptors due to the simplified generic urban forms, and linking these form descriptors to environmental performance (e.g. density related to energy use).

3. Reassessing the results using newly developed computer techniques

Daylight availability was introduced in Martin and March’s work by a convention, the ‘intercept rule’, which shares some characteristics with a view out of a building. Although the intercept rule led to attractive elementary mathematics (that could have been handled at that pre-computerised time), its physical meaning is debatable due to its simplifying assumptions. In fact, Lionel March himself, during a visit to Cambridge a few years ago, recklessly suggested employing our image processing techniques to reassess his results. Conclusions of the previous work might be disproved.

Thanks to technological advances during the last three decades, computing hardware and software have become more capable of handling large amounts of data in less time. Relatively large urban areas posed particular challenges due to the complexity of their representation. But recently, it was demonstrated that the simplest possible representation of urban texture is a figure-ground map. If scanned, the

resulting binary image tells us, for each pixel, whether it is built on, or open ground. If height information is included we obtain what geographers call a Digital Elevation Model (DEM), which is an image where each pixel has a grey-level proportional to the level of the urban surface. A DEM of an urban area in central London is shown in Fig. 8.

Urban form represented as a DEM can be analysed with image processing techniques using an image-processing package, such as the Matlab image processing toolbox. The innovation of these techniques lies in their integrated approach of looking simultaneously at key environmental performances such as solar radiation, energy consumption, wind environment and the effect of form on pollutant movement. Solar exposure—a key energy and comfort variable—will mainly be looked at in this paper.

Martin and March’s six archetypal forms in DEM format (Fig. 9) are analysed using these techniques. In order to reduce edge effect, each cluster or array consisted of nine buildings and only the central one was considered. Dimensions have been fixed following the work of Steemers et al. [5], and building height and width have been adjusted so that all forms have the same plot ratio of total floor space to site area. The number of parameters is further reduced by making the ratio of ‘potentially passive’ to ‘non-passive’ floor area the same throughout (‘potentially passive’ being the floor area within twice the floor to ceiling height from a façade, typically 6 m deep). Differences in environmental and energy performance due to variation in form or urban texture are consequently limited.

As a measure of daylight availability we have chosen the sky view factor. Values were computed on the ground and the façades at each 3 m height intervals. Then the average has been calculated in the central portion of the urban array, as shown in Fig. 10. Averages on façades were calculated (Table 1), the latter being representative of daylight condition in buildings.

Results did not clearly disprove Martin and Trace conclusions. More simply, astonishingly similar values were obtained. In fact, when we consider the view of the sky, there

Table 1
Average sky view factor on building façades in the archetypal forms described in Fig. 7

Height on façade (m)	Pavilions	Slab	Terraces	Terrace-courts	Pavilion-courts	Courts
0	0.44	0.46	0.46	0.41	0.42	0.39
3	0.45	0.47	0.48	0.43	0.45	0.43
6	0.47	0.48	0.50	0.46	0.47	0.49
9	0.48	0.49	0.52	0.51	0.50	0.62
12	0.49	0.50	0.54	0.61	0.54	
15	0.51	0.52	0.61		0.66	
18	0.52	0.54				
21	0.53	0.56				
24	0.55	0.60				
27	0.57	0.98				
30	0.62					
33	1.00					
Average	0.57	0.53	0.49	0.52	0.49	0.57

is a compensation between the favourably lower height of courts (more daylight), and their higher obstruction from lateral buildings.

The fact is that daylight distribution is relatively unaffected by urban form, when both built volume and passive to non-passive ratio are constant on a given site. This conclusion might have been expected, as it can be demonstrated with simple mathematics that the average view factor from the city to the sky is inversely proportional to the urban surface (roofs plus façades plus ground), and that these are quite stable under the geometrical conditions defined above.

4. Case study in a hot-arid climatic context

Although the beauty of Martin and March's approach owes much to its generality, it is widely accepted that the answer to the question "which urban forms make the best use of land?" cannot have an absolute answer. There are too many parameters to consider, each of which will have an effect. In the context of this paper, climatic variables should be considered. Moreover, when a large number of environmental variables is taken into account, it is likely that conflicts amongst them will emerge and so terms such as 'best' and 'optimum' embody value judgements that resolve conflicts. As stated by Oke [10], there are "almost infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives. Obviously there is no single solution, i.e. no universally optimum geometry". Despite this, there are predominant urban types that are associated with certain climate types, such as the courtyard type and the hot-arid climate.

4.1. The courtyard and hot arid climates

An abundance of literature claims that courtyards are an environmentally responsive building form for hot arid climates. This view is shared by amongst others Fathy [11] and Bahadori [12], who claim that the courtyard introversion fulfils several functions in hot arid regions: the creation of an outdoor yet sheltered space; the potential to exploit ingenious natural cooling strategies; the protection against wind-blown dust or sand; and the mitigation of the effects of solar excess. According to them—and many other scholars—climate appears to be one of the strongest determinants of architectural form. Fathy states: "By simple analysis it becomes quite understandable how such a pattern came to be universally adopted by the Arabs. It is only natural for anybody experiencing the severe climate of the desert to seek shade by narrowing and properly orienting the street, to avoid the hot desert winds by making the streets winding, with closed vistas".

Despite the apparent logic, most of these statements are vague and based largely on anecdotal monitoring, qualitative observation and common sense. How apt is the courtyard compared with alternative urban forms, such as the isolated

high or low-rise pavilions, that are colonising contemporary cities? How much better or worse is it in terms of response to climate?

We tried to answer such questions using image processing techniques. We calculated a number of environmental parameters following the Martin and March methodology but with two differences:

- (i) more environmental variables: examining different urban forms in the context of the hot-arid climate, which has helped us to identify the environmental variables of interest. These variables include surface to volume ratios, shadow densities, daylight accessibility and view factors from the city to the sky. They provide key measures related to solar radiation, thermal comfort and urban temperatures, which can be tested against the environmental conditions presented by hot-arid climates;
- (ii) real urban forms: considering more realistic urban types, which do not have the generality of Martin and March's ones. We start from a simplified courtyard type based on well-documented vernacular examples found in hot arid regions (as explained below) and subsequently mimic some transformation that might happen—and in many cases have happened—in real cities.

4.2. Description of the three urban forms

As in Martin and March's analysis, the governing principle is to take the same built volume and shape it according to different forms, which in turn are then simulated. These forms are described below.

The main case study selected for investigation is taken from a real prototype courtyard house. The specific configuration and dimensions of the courtyard house are adapted from a diagrammatic section of a courtyard urban dwelling as illustrated in Morris [13] (Fig. 11). An average number of three floors, each being 3 m high is assumed [14], and extrapolated to form a theoretical urban array (Fig. 12, left). Although, the real street network will generally be more irregular, this texture is representative of an Arabic city (Fig. 13).

The second two urban arrays are hypothetical yet fairly realistic pavilion types, mimicking potential modern urban



Fig. 11. Diagrammatic section of the selected base case courtyard. Dimensions based on Morris [13] and Talib [14].

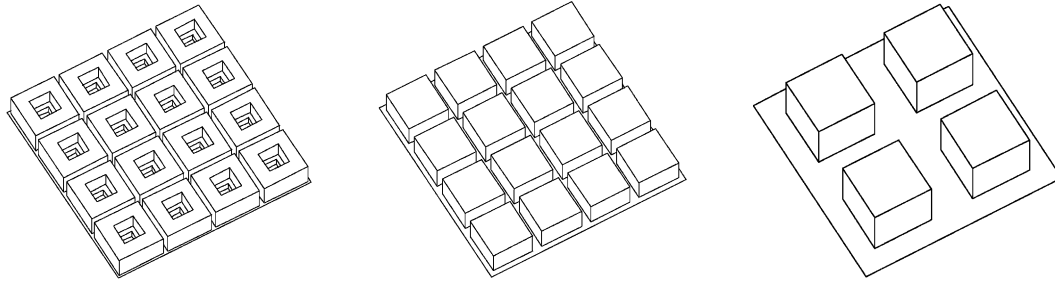


Fig. 12. Axonometric representation on a 67.5 m × 67.5 m site of the traditional Arabic courtyard (left: three floor courtyard) and of two pavilion structures (middle: micro-pavilion, three floors; right: pavilion, six floors).

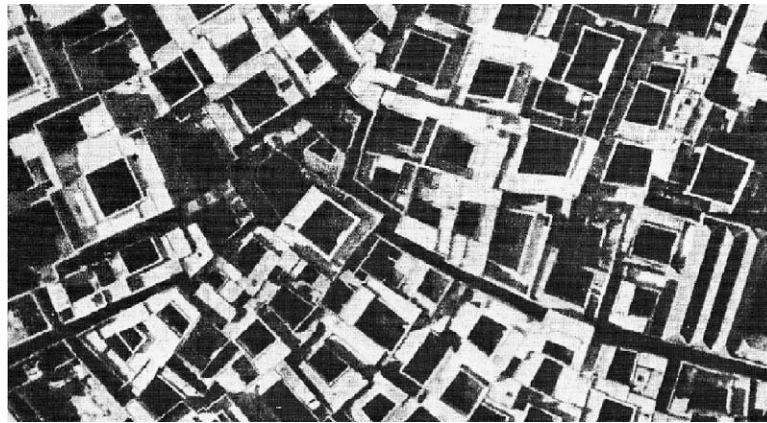


Fig. 13. Image of central Marrakech, showing the ‘courtyard’ urban fabric. Marrakech latitude 31.63°N, longitude 8.00°W [18].

replacements that typically take the place of or extend courtyard cities. The first variation (“pavilion 1”) consists of replacing each courtyard with an urban block centrally located in the initial plot, preserving the height of 9 m and obviously preserving the built volume. It is assumed that this option would be a pedestrianised modern urban neighbourhood with no vehicular traffic through the narrow streets (Fig. 12, middle).

The second variation (“pavilion 2”) represents a major urban regeneration intervention of integrating four courtyard plots into one urban block that could represent a mixed-use block (residential and offices). The street width is determined so as to accommodate two-way traffic, parking on the sides and a small sidewalk. Building height was calculated by maintaining the same total built volume as in the previous cases, which resulted in a height of six storeys—a realistic figure (Fig. 12, right).

All the case studies are shown as DEMs in Fig. 14 which overlays the plans in order to highlight their relative dimensional difference.

4.3. Analysis

Our analysis addressed the following parameters:

- (i) Surface to volume ratio, obtained by dividing the total surface of buildings (façades plus roofs) by their

volume, indicative of the building envelope surface which is exposed to the outside environment.

- (ii) Shadow density, a parameter based on detecting shadows on the ground at hourly intervals on a piece of city for a given day of the year. The average number of hours of shadows is then calculated at each point. For this parameter, a shadowing simulation was carried out for a summer day (21 June) at a latitude of 31°N, which corresponds to the latitude of the city of Marrakech.
- (iii) Daylight distribution, measured as ‘direct daylight factor’ values in streets. For this task the selected

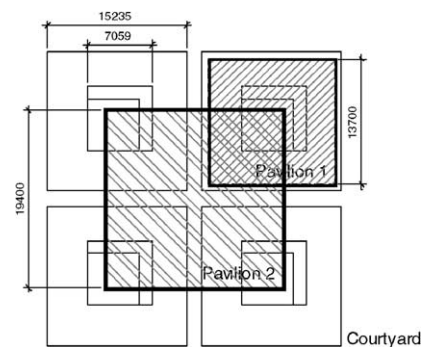


Fig. 14. Plan representation of the three cases of overlaid; note that a set of four courtyard houses are replaced by just one element in the second pavilion alternative.

Table 2
Numerical results from simulations

	Total surface (m ²)	Total volume (m ³)	Surface to volume ratio
Courtyards	15797	27030	0.584
Pavilion 1	10931	27030	0.404
Pavilion 2	7168	27030	0.265
Shadow density	Mean shadow density (average number of hours of shadow) on the ground on 21 June		
Courtyards	11.0		
Pavilion 1	9.8		
Pavilion 2	6.1		
Daylight distribution	Average normalised direct daylight factor at ground level		
Courtyards	10% in the street	19% in the courtyard	
Pavilion 1	30%		
Pavilion 2	53%		
Sky view factor	Average sky view factor at ground level	ΔT_{\max} urban–rural (°C)	
Courtyards	0.13	13.5	
Pavilion 1	0.23	12.1	
Pavilion 2	0.48	8.6	

model of the sky used for simulation is the standard CIE overcast sky, which represents “ideal” overcast conditions. Although, overcast sky conditions are not representative of prevailing sky conditions in hot-arid climates, which are normally clear, the nature of the simulation consists of investigating illuminance distribution only. The zenith is three times brighter than the horizon and the luminance distribution has cylindrical symmetry (i.e. it is solely dependent on the elevation). Values have been normalised in a similar manner to the sky component of the daylight factor (100% represents the illuminance that would fall on an unobstructed surface which sees the whole sky vault, 0% represents nil illuminance).

- (iv) Sky view factor, representing a good measure of the openness of the urban texture to the sky, often

associated, among other indicators, to the increase in temperature in the urban context compared with the surrounding rural context, referred to as the urban heat island phenomenon.

Numerical results for our three case studies are presented in Tables 1 and 2, while sky view factor images are grouped in Fig. 15.

4.4. Discussion of results

4.4.1. Surface to volume ratio

The surface to volume ratio is a rough indicator of urban grain size, representing the amount of exposed ‘skin’ of the buildings, and therefore, their potential for interacting with the climate through natural ventilation, day lighting, etc. However, the counter-indication to a high surface to volume ratio is the increase in heat loss during the winter season and heat gain due to exposure to solar radiation during the summer season.

Results show that the courtyard type has the higher surface to volume ratio (0.58). As for the smaller size pavilions (pavilion 1), their surface to volume ratio is a little higher than the larger pavilions (pavilion 2; 0.40 for the former compared to 0.27 for the latter). These results suggest that although the potential for natural ventilation and day lighting is higher, the courtyard type is also exposed to heat gain during summer and heat loss during winter. Comparing the horizontal and vertical surface areas between the courtyard and pavilion types for a constant volume reinforces this observation (façades: 803 m² for courtyard type and 493 m² for pavilion 1; roofs: 250 m² for courtyard type and 188 m² for pavilion 1).

In the light of the above hypothesis, the courtyard type would not seem to be performing thermally well. However, when the potential heat loss/gain during cold and warm seasons is analysed, respectively, within the complexity of hot-arid climatic context, results start to hint at sensible conclusions. In hot-arid climates night-time temperatures are typically significantly lower than day-time temperatures throughout the year. Summer diurnal temperature differences

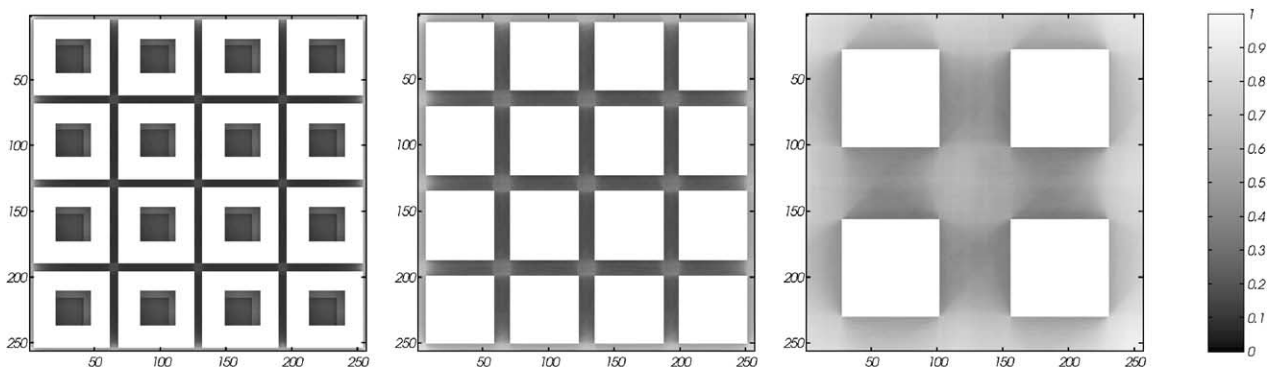


Fig. 15. Sky view factors from the street level for the three options presented in Fig. 14.

between the average daily maximum and minimum range between 15 and 19 °C (for Marrakech during the hot months of May–August). The winter months have a diurnal swing of approximately 3 °C and are relatively mild and sunny. Therefore, the critical months of the year are the hot months, and mitigating the temperature extremes of this season is a must. The ingenious solution of the courtyard house type in hot-arid climates is the use of high thermal mass to store heat through the expansive surface area during the day in order to benefit from it during the cooler nights. By maximising the surface to volume ratio, the courtyard acts as heat sink and therefore, limits extreme temperature stress, and re-radiates this heat indoors as well as to the night sky. Thus, the larger surface to volume ratio of courtyards, in combination with its thermal mass, is a positive advantage in the thermal performance of the building.

4.4.2. Shadow density and daylight distribution

Concerning the mean shadow density, high values recorded in the streets are beneficial in hot-arid regions as they provide protection to pedestrians and to the horizontal street surface from solar radiation. The courtyard type, which has the highest value, seems to be an advantaged configuration (11.0 compared to 9.8 for the pavilion 1 and 6.1 for the pavilion 2). As expected, high overshadowing also means low direct daylight availability, and the courtyard type, with its narrow streets, ranks dramatically lowest (15% mean value for courtyard type compared to 30% for pavilion 1 and 53% for pavilion 2). However, this observation seems to contradict the daylight benefits suggested through high surface to volume ratios, as explained above. It should be clarified that the shadow density reading in this case is taken in the streets and that the daylight values are an average of all ground surfaces (streets and courtyard floors). Taking the courtyard alone, the average day light factor is 19% (compared with the lower value of 10% in the street), which proves that daylight can be most effectively exploited via the courtyard and not via the external street façades. This observation corresponds well with the reality of this introverted house type that interacts with the climate through the courtyard, and is reinforced by the shallower plan depth that can exploit the courtyard environment, turning its back on a noisier and potentially more polluted street environment. Pavilion forms do not offer this ingenious facility of creating and exploiting an enhanced local microclimate.

However, we note here that our simulation simply takes into account light falling directly from the sky, and not that reflected from the ground and buildings, which in some cases can give a significant daylight contribution. An effective instrument to control daylight availability in cities is manipulating the surface reflectances; using white paint, for example, increases reflected light and therefore, overall illuminance values in the city. This reasoning is based on an interesting observation made with regard to the external surface colour of courtyard types in north African countries, such as Morocco which are generally painted with light

colours, with increasingly brighter tonalities at northern latitudes in south European contexts, such as in Greece, for example.

4.4.3. Sky view factor

Finally, the interpretation of the sky view factor values shows most interesting results. The values for our forms rank in the following increasing order: courtyard (0.13), pavilion 1 (0.23) and pavilion 2 (0.48).

A well known formula was introduced by Oke [15] and verified in a number of real cities, relating the maximum heat island temperature between urban and rural sites to the view factor from the middle of the street canyon floor and the sky.

$$\Delta T_{\max \text{ urban-rural}} = 15.27 - 13.88\psi_{\text{sky}}$$

where $\Delta T_{\max \text{ urban-rural}}$ is the maximum temperature difference and ψ_{sky} the sky view factor.

A preliminary observation of the results (maximum temperature differences of 8.6 °C for pavilion 2, compared to 12.1 °C for pavilion 1 and 13.5 °C for courtyard) would suggest that minimising the urban heat island would suggest sparse and scattered urban developments, with a high view factor. Is the courtyard thus a case of an inappropriate response to climate? Or could it be justified in urban climatology terms?

An extensive scientific literature shows that in hot arid climates a low sky view factor is beneficial. Looking at the urban heat island phenomenon in more detail, it is often described using average temperatures [16], thus masking peaks. The urban heat island usually presents two of them: a maximum during the night and a minimum during the day, often described as an 'urban cool island'. In hot arid climates night-time temperatures are usually significantly lower than day-time temperatures, and an increase in temperature would probably be welcomed at night if concomitantly extreme temperature stress during the day is alleviated.

As comfort is not only based on temperature, but also significantly on radiative exchange, this is where the benefit of low sky view factors comes into play again, especially during day-time hours when people are outdoors in the streets and courts, and comfort is crucial. During day-time hours, low sky view factors insure an increase in direct shading and a reduction in reflected radiation.

So again, despite the initial indication of thermal analysis, the courtyard form presents characteristics that when consider in an integral way can significantly improve the environmental performance.

5. Conclusions

Martin, March and Trace's ingenious approach at analysing the urban built form through generic simplified yet very representative forms has instigated an on-going wave of interest among various scholars as shown throughout this

paper. Their initial question of land-use optimality of urban form has motivated others, including us, to extend the search and broaden the question. In the process, innovative application of tools, such as image processing techniques offering an integrated insight of the environmental behaviour of urban built form are put to use. These tools shed light on the intricacy of environmental consequences that different urban configurations could trigger. Moreover, the added complexity of the climatic context presents a multi-dimensional problem to be approached cautiously.

As demonstrated in the above case study, the specification of the climatic zone within which any environmental research on urban form is taking place is fundamental in the analysis of results. The latter remain as givens and can only be interpreted within the climatic context. The case study demonstrated that the courtyard configuration showed better response through the calculated environmental variables (surface to volume ratio, shadow density, daylight distribution, sky view factor) than the pavilion types 1 and 2 in the specific context of hot-arid climates. The courtyard type would not be a good option in hot humid climates such as tropical ones, where a narrow daytime temperature variation would not benefit from thermal mass and suffer from an even slight increase in the urban heat island. Reassuringly enough, courtyards are not generally found in vernacular tropical architecture.

Beyond climate, another important factor to take into consideration is that of built proportions. The findings do not show that all courtyards behave better than all pavilions; just that a given courtyard behaves better than a given pavilion. Changes in proportions can trigger radical variations: [17], for instance, hints that large courtyards are environmentally adequate in cold climates, where under certain geometrical conditions they can act as sun concentrators and retain their sheltering effect against cold winds.

Finally, as everywhere else throughout this study, our primary interest was in urban geometry. Many parameters have not been taken into account directly in the analysis, such as thermal mass and surface reflectance. Both can reveal themselves as critical factors: in the courtyard case, although low illuminance levels were calculated in the street, better values were seen in the courtyard itself. Pedestrian thermal comfort seems therefore to have been of higher priority than direct daylight availability.

“What building forms make the best use of land?” If ‘best’ is interpreted in environmental terms without sacrificing floor space for a given plot of land, then the answer for hot arid climates is the courtyard form. The combinations of

- (i) larger surface area and high thermal mass,
- (ii) daylight via the courtyard and shallow plan form,
- (iii) narrow spaces for shade and improved thermal comfort despite increased heat island,

create a context where low energy strategies through the limitation of air conditioning loads are possible. A primary characteristic of this is that courts can create a microclimate

in the form of an intermediate environment that will be more quite, clean and more private than the street. The result is that the surrounding interior spaces can interact positively with this improved microclimate. One can speculate that even in temperate and cool climates many of these characteristics of courts will make them the “building forms that make the best use of land”, particularly in an urban context.

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